MIT Technology Review

VOL. 117 NO. 6 NOVEMBER/DECEMBER 2014 $6.99

Inequality

p52

From the Editor

GUIDO VITTI

AT 2:15 P.M. ON AUGUST 31, 1910, COLONEL Roosevelt (as the ex-president, proud of his "crowded hour" on San Juan Hill, preferred to be known) climbed onto a kitchen table in a grove near Osawatomie, Kansas, and delivered the most radical speech of his life.

Recalling the scene, Edmund Morris, in the third volume of his biography, writes, "A crowd of thirty thousand Kansans waited to hear him declaim his 'credo.' The prairie sun was strong, but there had been a cloudburst earlier in the day, and many stood ankle deep in mud."

Where the abolitionist John Brown had fought the Missouri raiders in 1856, Theodore Roosevelt invoked the Civil War veterans who were seated before him. He said, "All I ask in civil life is what you fought for in the Civil War."

What did TR want? "I ask that civil life be carried on according to the spirit in which the army was carried on. Nobody grudged promotion to Grant or Sherman ... because they earned it." He called for "practical equality of opportunity for all citizens," and he described how it might be achieved. "The really big fortune, the swollen fortune, by mere fact of its size acquires qualities which differentiate it in kind as well as in degree from what is possessed by men of relatively small means." Roosevelt called for graduated income and inheritance taxes. He wanted "combinations in industry" to be controlled in the interest of the public welfare. Corporations were to be denied suffrage. "I stand for the square deal!" he thundered.

It is impossible to imagine any American politician today delivering Roosevelt's "New Nationalism" speech. It was written (mostly by a progressive forester named Gifford Pinchot) in reaction to the economic inequality of the Edwardian age.

But the distance between rich and poor today is as unsettling as the inequality that TR worried would erode collective faith in institutions and offend the public's sense of fairness. No one knows why contemporary inequality has become so savage, although everyone knows it is so. Wages for low- and middle-income workers have been flat or declining since the 1970s, even as the rich have captured the spoils of swelling economies. (In the United States, the richest 1 percent enjoys 34 percent of the wealth.) There is a common sense that technology is responsible for our unequal lots, because automation eliminates good jobs while requiring new skills from workers ill-equipped to learn them. People worry that the technological economy, exemplified by Silicon Valley, rewards a very few obscenely. In "Technology and Inequality" on page 52, David Rotman, *MIT Technology Review*'s editor, explores the debate among economists about how technology contributes to income disparities, explains why—beyond simple justice—we should care about inequality, and describes what might be done to fix it.

An income tax on individuals was ratified by the U.S. Congress in February 1913; after the Second World War, a more progressive tax functioned as a brake upon inequality until President Reagan cut tax rates.

In our own time, Rotman suggests, reimagining education might address the causes of inequality. Roosevelt accepted merit-based inequality. That's the American way. But TR said practical equality of opportunity would have this virtue: "Every man will have a fair chance to make of himself all that in him lies; to reach the highest point to which his capacities, unassisted by special privilege of his own and unhampered by the special privilege of others, can carry him."

We care about inequality because it is wasteful of human capital, which is to say of lives. A technology publication takes inequality as its subject because insofar as technology has contributed to inequality, it may be part of the solution, too.


Who will bring
our electrical grid
out of the Dark Ages?

Contents

Mummified deer leg, sealed in beeswax.
p. 72

November/December 2014

ON THE COVER

Illustration by R. Kikuo Johnson


Who will drive
the future of the
transportation industry?
You and NI will. From passenger vehicles to rail systems, the transportation industry is struggling to deal with increased electronic complexity, higher demands on safety, and accelerated time-to-market requirements. See how NI helps simplify rapid control prototyping, in-vehicle data logging, and a variety of other critical applications at ni.com.
NATIONAL INSTRUMENTS™
©2014 National Instruments. All rights reserved. National Instruments, NI, and ni.com are trademarks of National Instruments.
Other product and company names listed are trademarks or trade names of their respective companies. 18586

Editor in Chief and Publisher
Jason Pontin

EDITORIAL

Editor
David Rotman

Deputy Editor
Brian Bergstein

News and Analysis Editor
Will Knight

Chief Correspondent
David Talbot

San Francisco Bureau Chief
Tom Simonite

Senior Editor, Materials
Kevin Bullis

Senior Editor, Business Reports
Nanette Byrnes

Senior Editor, MIT News
Alice Dragoon

Senior Editor, Mobile
Rachel Metz

Senior Editor, Biomedicine
Antonio Regalado

Senior Web Producer
Kyanna Sutton

Managing Editor
Timothy Maher

Copy Chief
Linda Lowenthal

Research Editor
Mike Orcutt

Special Projects Editor
Kristin Majcher

Associate Web Producer
J. Juniper Friedman

Production Director
James LaBelle

Contributing Editors
Katherine Bourzac
Jon Cohen
Peter Fairley
Simson L. Garfinkel
Robert D. Hof
Courtney Humphries
Martin LaMonica
Amanda Schaffer

DESIGN

Creative Director
Nick Vokey

Deputy Art Director
Colin Jaworski

Art Assistant
Lynne Carty

CORPORATE

President
Kathleen Kennedy

Chief Financial Officer
Rick Crowley

Chief Operating Officer
James Coyle

Director of International Business Development
Antoinette Matthews

Executive Assistants
Giovanna Bortolamedi
Leila Snyder

Manager of Information Technology
Colby Wheeler

Office Manager
Linda Cardinal

PRODUCT DEVELOPMENT

Chief Digital Officer and VP, Product Development
Erik Pelletier

Product Manager, Events and Special Projects
Vanessa DeCollibus

Senior Software Engineers
Shaun Calhoun
Molly Frey
Jason Lewicki

User Interface/Digital Designer
Emily Dunkle

EVENTS

Executive Producer
Chris Shipley

VP, Events and Strategic Partnerships
Amy Lammers

Director of Events Programming
Laura Janes Wilson

Event Operations Manager
Gerri Powers

Senior Content Producer
Marcy Rizzo

Event Coördinator
Lina Umansky

CONSUMER MARKETING

VP, Consumer Revenues and Marketing
Bruce Rhodes

Director of Marketing and Communications
David W.M. Sweeney

FINANCE

General Ledger Manager
Olivia Male

Accountant
Letitia Trecartin

BOARD OF DIRECTORS

Reid Ashe
Judith M. Cole
Jerome I. Friedman
Israel Ruiz

ADVERTISING SALES

Director of Advertising Sales
James Friedman
james.friedman@technologyreview.com
617-475-8015

Midwest Sales Director
Maureen Elmaleh
maureen.elmaleh@technologyreview.com
303-975-6381

New England, Detroit, and Canada
Barry Echavarria
barry.echavarria@technologyreview.com
603-924-4546

Mid-Atlantic and Southeast
Clive Bullard
cbullards@cs.com
845-231-0846

West Coast
Rob Finley
rob.finley@technologyreview.com
415-659-2982

Europe
Anthony Fitzgerald
mail@afitzgerald.co.uk
44-1488-680623

France
Philippe Marquezy
philippe.marquezy@espacequadri.com
33-1-4270-0008

Germany
Michael Hanke
michael.hanke@heise.de
49-511-5352-167

China
Tao Lin
imlintao@hotmail.com

Japan
Akiyoshi Ojima
ojima@media-jac.co.jp
813-3261-4591

Spain and South America (Online)
Pedro Moneo Laín
pedro.moneo@opinno.com
34-667-732-894

Advertising Services Coördinator
Ken Collina

Sales & Marketing Associate
Julie Swanson

Custom Editor
Anne Stuart

Advertising Services
webcreative@technologyreview.com
617-475-8004

Media Kit
www.technologyreview.com/media

MIT ENTERPRISE FORUM, INC.

Executive Director
Antoinette Matthews

Director of Chapter Leadership and Process
Gaylee Duncan

Director of Communications
Joyce Chen

Chairman
Jason Pontin

President
Kathleen Kennedy

Treasurer
James Coyle

CUSTOMER SERVICE AND SUBSCRIPTION INQUIRIES

National: 800-877-5230

International: 903-636-1115

E-mail: technologyreview@pubservice.com

Web: www.technologyreview.com/customerservice

MIT Records: 617-253-8270 (alums only)

Reprints: Donna Summers
dsummers@wrightsmedia.com
281-419-5725

Licensing and permissions:
licensing@technologyreview.com

Technology Review
One Main Street, 13th Floor
Cambridge, MA 02142
Tel: 617-475-8000

The mission of *MIT Technology Review* is to equip its audiences with the intelligence to understand a world shaped by technology.

Technology Review, Inc., is an independent nonprofit 501(c)(3) corporation wholly owned by MIT; the views expressed in our publications and at our events are not always shared by the Institute.

De Technologia non multum scimus. Scimus autem, quid nobis placeat.


Who will fuel the future of oil and gas?
You and NI will. Now more than ever, petroleum companies are relying on advanced technology to help meet increasing energy needs and ensure reliability in extraction, monitoring, and distribution. See how NI provides a variety of solutions for this critical industry at ni.com.
NATIONAL INSTRUMENTS™
©2014 National Instruments. All rights reserved. National Instruments, NI, and ni.com are trademarks of National Instruments.
Other product and company names listed are trademarks or trade names of their respective companies. 18586

Feedback

E-mail letters@technologyreview.com

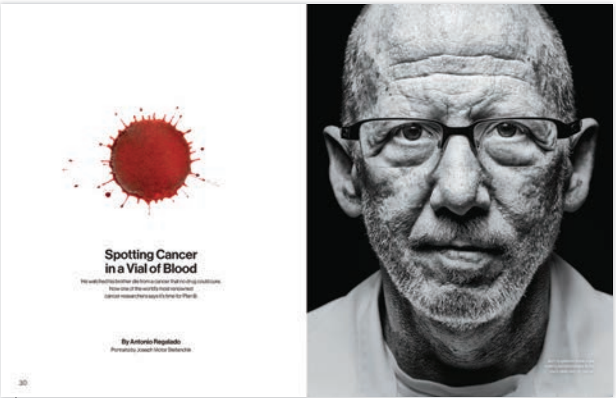
Write *MIT Technology Review*
One Main Street, 13th Floor
Cambridge, MA 02142

Please include your address, telephone number, and e-mail address.

Letters and comments may be edited for both clarity and length.

Five Most Popular Stories

MIT Technology Review
Volume 117, Number 5



1 Spotting Cancer in a Vial of Blood

Will this testing become so mainstream and inexpensive that it becomes standard operating procedure for most physicians, and will insurance companies pay for the screening procedures? After all, there's $90+ billion spent every year on treating cancer. Will doctors and hospitals want to kill such a cash cow? **—mkogrady**

I am so tired of the line of thinking that says we should not find early disease because some docs will handle the situation less than optimally. We are not supposed to run the world or our lives based on bad doctors. **—kirklsp**

2 In Praise of Efficient Price Gouging

Uber's pricing strategy is doomed to fail in NYC because we have so many alternatives. Gouge me on price and I have car services, taxis, buses, and subways. My first ride on Uber was a price gouge, as the driver billed me for a mistake he made in finding the address. **—abekohen**

@abekohen I had the reverse experience. It's impossible to get a cab between 4 and 6 P.M. in Manhattan. Car services promise to pick you up at a certain time but fail because they're "busy." I'd rather pay more to get to an event or meeting than miss it. **—lambdafunds**

3 A Chinese Internet Giant Starts to Dream

The Chinese population is twice that of the U.S. and Europe combined, so when we talk about Baidu having 75 percent market share, we are talking about the equivalent of 100 percent market share in the U.S., Japan, Germany, and France, and that's with just 50 percent Internet penetration in China. And when we talk about Baidu "looking inwards," it's good to remember the "inside" for Baidu is already bigger than what many consider the "outside," and the inside is getting bigger.
—vlhcvlhc

4 The History Inside Us

Someday, with computational power currently beyond our imagination, we will be able to reconstruct vast swaths of detailed history going back to our deepest origins by mathematically deriving from our genomes. Empires we never knew existed will be deduced; migrations not yet known; whole cultures living for thousands of years, all traces of which have been lost to time except for what they gave to our DNA. Breathtaking.
—Rigatoni

5 Data-Driven Health Care

Data-driven health care has its limits—human limits. The data is a good benchmark, but it all comes down to human interaction. So far, a robot cannot diagnose a broken bone or cancer. Data is just a tool among all us other living things. **—Julia Walden**

The electronic medical record is designed to track "points" useful in billing. If done in real time, it distracts the clinician, who can no longer keep eye contact with the patient. If done at the end of the day, it's an imposition on the clinician and subject to memory lapses.
—frank.finkelstein.7

Useless Nation

Regarding Mattathias Schwartz's "Love of Labor," about the erosion of human skills: What we now call white-collar jobs evolved from trade. The East India Company needed armies of clerks to record payments for the transfer of goods. A college in Hertfordshire, England, was created to train these clerks, and it was the blueprint for our education systems in Europe and America.

Meanwhile work on the ships, on the land, and in industry was hard. So the message became: "Become educated and it will lead to a better life" (i.e., learn to read and count or you'll be stuck in the horrid machine jobs). This made learning actual skills unfashionable. It became a vanity thing. You could say you knew about Shakespeare, or art, or philosophy, while practical skills were seen as below "educated" people.

Now we have nations of educated people with no skills other than to do "services." And the value of knowledge is plummeting in a world where answers are clicks or swipes away. Our vanity has made a whole nation, or even a quarter of the planet, more or less useless.

—PeterJ42

Machine Learning

Interesting graphic ("Robots Rising") in your Upfront section. Nearly two centuries ago the Luddite movement arose to combat the displacement of mill workers with machines; workers feared increased automation would lead to massive unemployment. Fifty years later small farmers lost their livelihoods as machinery replaced them. The same situation is now occurring on the factory floor with robots. Short-term, the layoffs create great hardship. Long-term, the automation provides cheaper goods for consumers and higher wages for workers as productivity rises. History repeats itself.

—wcordell2

Views

David Farber

Karrie Karahalios

Bryan Ford

COMMUNICATIONS

The Wrong Fix

Want regulations to preserve the open Internet? Be careful what you wish for.

DEMANDS FOR NETWORK NEUTRALITY have reached fever pitch in Washington, D.C., as many voices stress the need for the Federal Communications Commission to save our open Internet. They claim that broadband Internet service providers can block data flow from selected websites, charging content providers for delivering content to customers and establishing paid "fast lanes" for some and slow lanes for everyone else (see "The Right Way to Fix the Internet," page 28). Is the Internet suddenly in great danger?

The term "network neutrality" was coined by a legal scholar in 2002, harking back to the seminal paper "End-to-End Arguments in System Design," which called for network operators to be "dumb pipes" carrying the bits they are given with no changes whatsoever. After decades of pledging "hands off the Internet," the FCC took up the network neutrality challenge and issued its first order in 2010. Although only two violations had been documented, the FCC went ahead with "prophylactic" regulations. This order was struck down by the D.C. Circuit Court on jurisdictional grounds, and the FCC is going back for a second round, leading to the current brouhaha.

In the first order, the FCC ruled that ISPs could not block or delay content and could not discriminate among content providers—none would be allowed to pay for priority delivery of their traffic. The regulators' view was that these rules simply reflected current best practices among ISPs. If that's true, the FCC was at the very least freezing the current status of the dynamic Internet, ensuring that this constantly evolving network could evolve no more. But was the FCC's view even correct? David Clark of MIT, an early chief protocol architect of the Internet, recently said that "the network is not neutral and never has been," dismissing the assumptions of net neutrality supporters as "happy little bunny rabbit dreams." Early Internet operators routinely discriminated in favor of traffic that was sensitive to latency, and similar options are available today. The phenomenal success of the Internet suggests that the technologists who have been running it really don't need help.

But what could go wrong if the FCC decides to put a few rules in place? Plenty. As Gerald Faulhaber of the University of Pennsylvania has shown, the history of telecommunications regulation tells a sorry story of glacial decision-making focusing on yesterday's problems, inhibition of innovation, and, worst of all, what economists call "rent-seeking"—businesses' use of the regulatory process to put their competitors at a disadvantage.

Yes, the open Internet is in danger. But not from lack of neutrality—from the prospect of the FCC regulating it like a 20th-century utility.

David Farber, former chief technologist for the FCC, is an emeritus professor at the University of Pennsylvania.

WEB

Algorithm Awareness

How the news feed on Facebook decides what you get to see.

INCREASINGLY, IT IS ALGORITHMS THAT choose which products to recommend to us and algorithms that decide whether we should receive a new credit card. But these algorithms are buried outside our perception. How does one begin to make sense of these mysterious hidden forces?

The question gained resonance recently when Facebook revealed a scien-

SAM KERR

tific study on "emotion contagion" that had been conducted by means of its news feed. The study showed that displaying fewer positive updates in people's feeds causes them to post fewer positive and more negative messages of their own. This result is interesting but disturbing, revealing the full power of Facebook's algorithmic influence as well as its willingness to use it.

To explore the issue of algorithmic awareness, in 2013 three colleagues and I built a tool that helps people understand how their Facebook news feed works.

Using Facebook's own programming interface, our tool displayed a list of stories that appeared on one's news feed on the left half of the screen. On the right, users saw a list of stories posted by their entire friend network—that is, they saw the unadulterated feed with no algorithmic curation or manipulation.

A third panel showed which friends' posts were predominantly hidden and which friends' posts appeared most often. Finally, the tool allowed users to manually choose which posts they desired to see and which posts they wanted to discard.

We recruited 40 people—a small sample but one closely representative of the demographics of the U.S.—to participate in a study to see how they made sense of their news feed. Some were shocked to learn that their feed was manipulated at all. But by the end of our study, as participants chose what posts they wanted to see, they found value in the feed they curated.

When we followed up months later, many said they felt empowered. Some had changed their Facebook settings so they could manipulate the feed themselves. Of the 40 participants, one person quit using Facebook altogether because it violated an expectation of how a feed should work.

The public outcry over Facebook's emotion study showed that few people truly grasp the way algorithms shape the world we experience. And our research shows the importance of empowering people to take control of that experience.

We deserve to understand the power that algorithms hold over us, for better or worse.

Karrie Karahalios is an associate professor of computer science at the University of Illinois.

COMPUTING

Open Surveillance

Cryptography could keep electronic investigations under control.

DEMOCRACY RESTS ON THE PRINCIPLE that legal processes must be open and public. Laws are created through open deliberation; anyone can read or challenge them; and in enforcing them the government must get a warrant before searching a person's private property. For our increasingly electronic society to remain democratic, this principle of open process must follow us into cyberspace. Unfortunately, it appears to have been lost in translation.

The National Security Agency, formed after World War II to spy on wartime adversaries, has clung to military-grade secrecy while turning its signals-intelligence weapons on us and our allies. While nominally still a "foreign intelligence" agency, the NSA has become a de facto law enforcement agency by collecting bulk surveillance data within the United States and feeding the data to law enforcement agencies. Other agencies also have secret-surveillance fever. The FBI secretly uses warrantless subpoenas to obtain bulk cell-tower records affecting hundreds of thousands of users at once, whether investigating bank robberies or harmless urban pranks. Police spy on entire neighborhoods with fake cellular base stations known as "StingRays" and have deliberately obfuscated warrants to conceal their use of the technology.

All this secrecy harms our democracy. But effective surveillance does not require total secrecy. It can follow an openness principle: any surveillance process that collects or handles bulk data or metadata about people who are not specifically targeted by a warrant must be subject to public review and should use strong encryption to safeguard the privacy of the innocent. To gain access to unencrypted surveillance data, law enforcement agencies must identify people whose actions justify closer investigation and then demonstrate probable cause. The details of an investigation need not be public, but the data collection process should be—what was collected, from whom, and how it was decrypted. This is no different from the way the police traditionally use an open process to obtain physical search warrants without publicly revealing details of their investigation.

Technology that my colleague Joan Feigenbaum and I and our research group have developed could allow law enforcement officials to enact this approach without hampering their work. In fact, it could even enhance it. Modern cryptography could let agencies surgically extract warrant-authorized data about people of interest while guarding the privacy of innocent users. In the case of bank robbers known as the High Country Bandits, the FBI intercepted cell-tower records of 150,000 people to find one criminal who had carried a cell phone to three robbery sites. Using our encrypted search system, the FBI could have found the bandit's number without obtaining data on about 149,999 innocent bystanders.

It's better to risk that a few criminals will be slightly better informed than to risk the privacy and trust of everyone.

Bryan Ford is an associate professor of computer science at Yale University.

Upfront

On the Horns of the GMO Dilemma

Can genome-editing technology revive the idea of genetically modified livestock?

By Antonio Regalado

NEIL WEBB

Upfront

QUOTED

"Dealing with the privacy and security aspects of the Internet of things is going to be one of the biggest challenges we have faced in security for a long time."

— Marc Rogers, principal security researcher with mobile security company Lookout.

Four years ago, Scott Fahrenkrug saw an ABC News segment about the dehorning of dairy cows, a painful procedure that makes the animals safer to handle. The shaky undercover video showed a black-and-white Holstein heifer moaning and bucking as a farmhand burned off its horns with a hot iron.

Fahrenkrug, a molecular geneticist then at the University of Minnesota, thought he had a way to solve the problem. He could create cows without horns. He could save farmers money. And by eliminating the dairy industry's most unpleasant secret, he might even score a public relations success for genetic engineering.

The technology Fahrenkrug believes could do all this is called gene editing. A fast, precise new way of altering DNA, it's been sweeping through biotechnology labs. Researchers have used it to change the genes of mice, zebrafish, and monkeys, and it is being tested as a way to treat human diseases like HIV.

With livestock, gene editing offers some extraordinary possibilities. At his startup, Recombinetics, located in St. Paul, Minnesota, Fahrenkrug thinks he can create blue-ribbon dairy bulls possessing traits not normally found in those breeds but present in other cattle, such as lack of horns or resistance to particular diseases. Such "molecular breeding," he says, would achieve the same effects as nature might, only much faster.

That could upend the global livestock industry. Companies could patent these animals just as they do genetically modified soybeans or corn. Entrepreneurs are also ready to challenge the U.S. Food and Drug Administration, which has never approved a GMO food animal. They say gene editing shouldn't be regulated if it's used to merely swap around traits within a species. "We're talking about genes that already exist in a species we already eat," says Fahrenkrug.

The use of the technology remains experimental and far from the food chain. But some large breeding companies are starting to invest. "There may be an opportunity for a different public acceptance dialogue and different regulations," says Jonathan Lightner, R&D chief of the U.K. company Genus, which is the world's largest breeder of pigs and cattle and has paid for some of Recombinetics' laboratory research. "This isn't a glowing fish. It's a cow that doesn't have to have its horns cut off."

To date, GMO food animals have been a complete bust. After the first mice genetically engineered with viral DNA appeared in the 1970s, a parade of other modified animals followed, including sheep that grow extra wool thanks to a mouse gene, goats whose udders made spider silk, and salmon that mature twice as quickly as normal. But such transgenics—animals incorporating genes from other species—mostly never made it off experimental farms. Cows edited to be hornless would not have DNA from a different species, just from a different breed of cattle. That is what entrepreneurs hope will create a regulatory loophole. The FDA's regulations on genetically engineered animals, issued in 2009, didn't anticipate gene editing and, in Fahrenkrug's opinion, may not cover it.

"We haven't realized the opportunity for genetic engineering in animals to any degree."

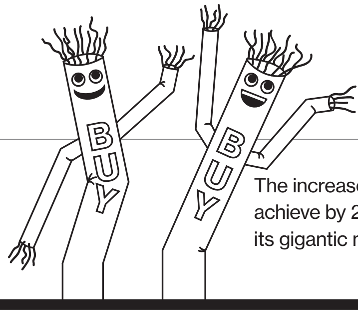
In response to questions from *MIT Technology Review*, the FDA agreed that its rules "addressed the technology at the time." But the agency says it reserves the right to regulate gene editing, too. "We are carefully considering the appropriate regulatory approach for products made using this technology but have not reached any decisions," said agency spokeswoman Theresa Eisenman.

To make hornless dairy cows, Fahrenkrug says, he looked up the genetic sequence that naturally causes Angus cattle, a beef variety, to lack horns. Following nature's no-horns recipe, he used a gene-editing method called TALENs in his lab to introduce it into skin cells from a horned Holstein bull. In total, he deleted 10 DNA letters and, in their place, added 212. Some of those cells were then turned into embryos through cloning and used to impregnate several cows. Fahrenkrug is expecting the first of several hornless calves to be born within a few weeks. He declined to say where they were being kept, citing the risk of sabotage by animal-rights or anti-GMO activists.

Any genetic tinkering with the food supply could arouse opposition, but Fahrenkrug hopes the vision of a naturally hornless cow could make people see things his way. Animal-rights campaigners hate GMOs. But they hate dehorning more. Farmers do it only because they have to. Douglas Keeth, an investor in Recombinetics, says his great-grandmother was gored to death by a dairy cow. "When I was a young man working on a farm, we'd dehorn cattle with mechanical means. You

COURTESY OF MARC ROGERS | IAN CHO

Upfront



1,000%

The increase in car sales Tesla will need to achieve by 2020 to maintain full production at its gigantic new battery factory in Nevada.

The genome of the Nelore bull on the right was edited to produce 30 percent more muscle fiber.

do 100 steers and, well, it's a bloody mess," he says. "You wouldn't want to show that on TV."

Although not all cattle have horns, most Holsteins do. According to the Holstein Association USA, all 30 of the top-rated Holstein bulls in the U.S. have horns. Semen from these champion bulls, which are prized for fathering offspring that produce titanic amounts of milk, is frozen and shipped around the globe. After more than a century of selective breeding, the average dairy cow in the U.S. produces 23,000 pounds of milk a year (compared with about 5,000 pounds for an ordinary cow).

With Holsteins smashing milk records, any effort to mix in new traits by mating is challenging. That's because crossing a record milker with a lesser animal will dilute its pedigree, says Lightner, whose company shipped $177 million worth of frozen bull semen last year. It can take several generations of crosses to make a true milk champion again.

Gene editing, by contrast, is fast and precise. Last year, working with the Roslin Institute and Texas A&M University, Fahrenkrug easily created Brazilian Nelore cattle with increased muscle mass. He did that by adding to Nelore embryos a muscle-boosting mutation that occurs naturally in breeds like Belgian Blues, though it had never before been seen in rangy, heat-tolerant Nelores.

Lightner says such feats are why Genus has started underwriting gene-editing research. "We haven't realized the opportunity for genetic engineering in animals to any degree," he says. "But these new approaches that let us move traits around could be transformational."

Fahrenkrug's ideas have grabbed the attention of dairy farmers, too. The technology "is very cool," says Tom Lawlor, head of R&D for the Holstein Association USA. But he says milk producers are afraid of genetic engineering. "The technology definitely looks promising and seems to work, but we would enter into it slowly as opposed to rapidly for fear the consumer would get the wrong idea," he says. "We get scared to death, because our product is milk, and it's wholesome."

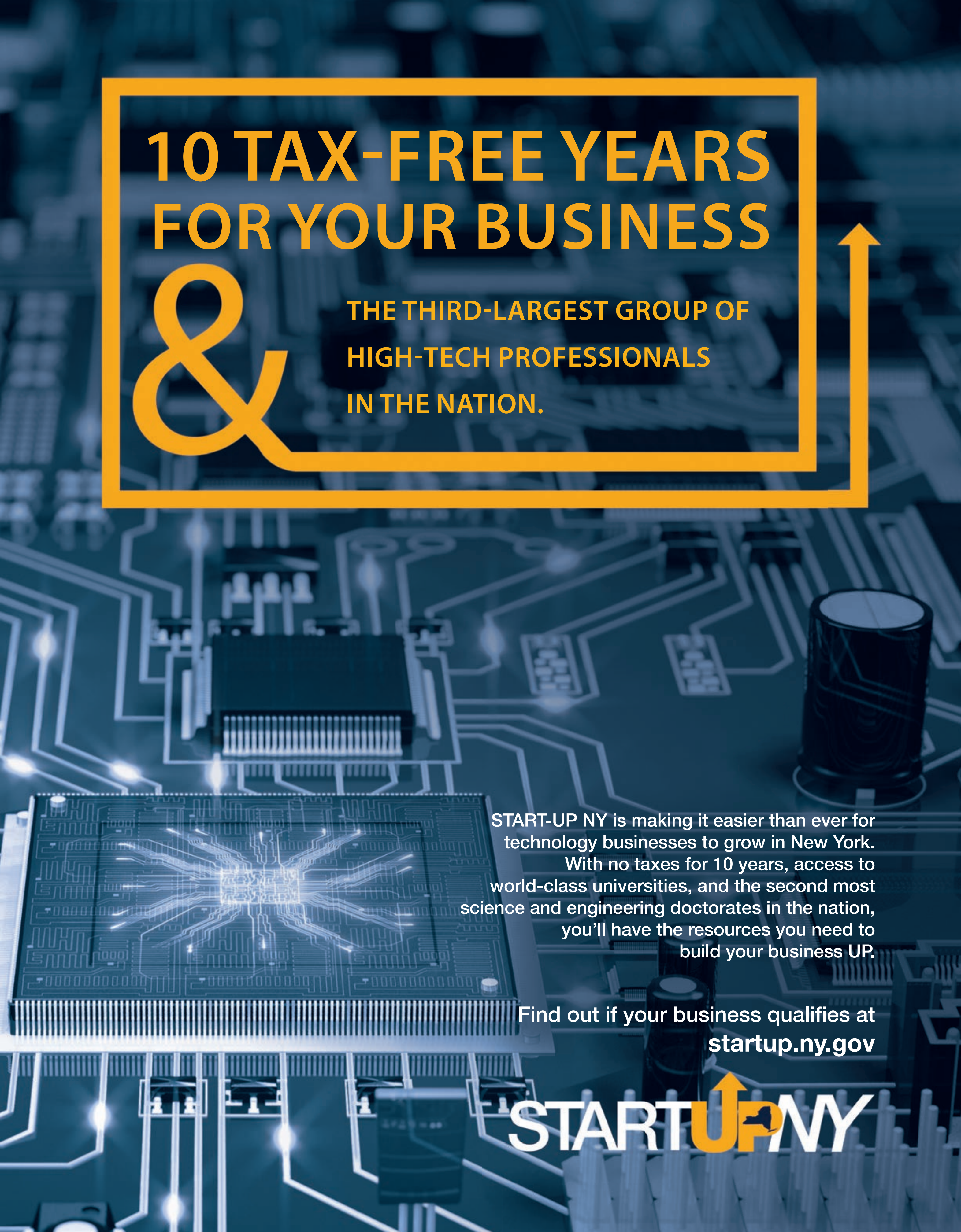
In January, Fahrenkrug filed a patent application laying claim to any animal whose genes are edited to remove their horns. The threat of cattle patents has alarmed some farmers already distressed by seed patents. "They could take semen from my bull, gene-edit it, patent it, and the farmer will get totally screwed," says Roy MacGregor, who breeds hornless cattle in Peterborough, Ontario. "They should not be allowed to."

Anti-GMO campaigners also won't have to look far for reasons to criticize gene editing. There are easy targets, like a strategy Fahrenkrug conceived to prevent cattle from reaching sexual maturity. That may make it quicker to fatten them for slaughter. It would also allow gene-editing companies to keep selling animals without the risk of "uncontrolled breeding of the animals by the buyers," as another of Recombinetics' patent applications puts it.

It's possible, even probable, that cautious regulators, activists, and commercial challenges will keep products from gene-edited animals off supermarket shelves for years—maybe forever. But what's not slowing down is the advance of gene-editing technology. "People will say to me, 'You realize this changes everything, don't you?' Because it does," says Fahrenkrug. "The genome is information. And this is information technology. We have gone from being able to read the genome to being able to write it."

"They could take semen from my bull, gene-edit it, patent it, and the farmer will get totally screwed."

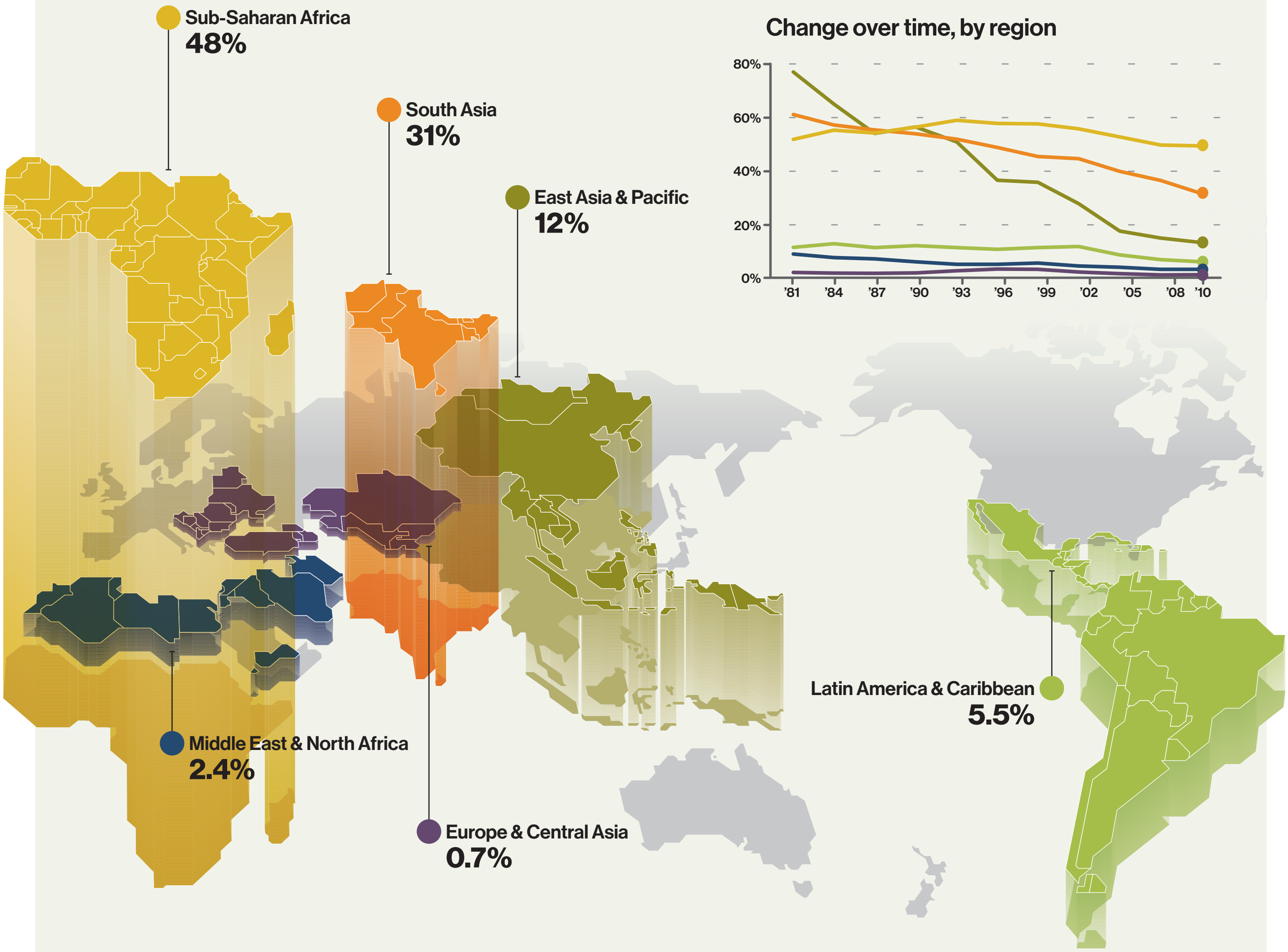
COURTESY OF RECOMBINETICS


10 TAX-FREE YEARS
FOR YOUR BUSINESS
&
THE THIRD-LARGEST GROUP OF
HIGH-TECH PROFESSIONALS
IN THE NATION.
START-UP NY is making it easier than ever for technology businesses to grow in New York. With no taxes for 10 years, access to world-class universities, and the second most science and engineering doctorates in the nation, you'll have the resources you need to build your business UP.
Find out if your business qualifies at
startup.ny.gov
STARTUPNY

Upfront

The Extremes of Inequality

While only the rich are enjoying significant income growth in the United States (see “Technology and Inequality,” page 52), fortunes have generally improved for the world’s poorest people—though there is still far to go. Here is the percentage of people in each region who live on **$1.25 or less per day**.



Then and Now
Extreme poverty has declined with development, but war and instability defy that trend.

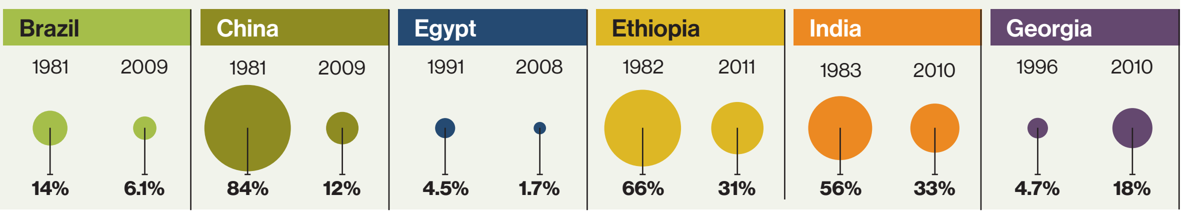


ILLUSTRATION BY WALTER BAUMANN
DATA FROM WORLD BANK; $1.25 FIGURE IS ADJUSTED FOR PURCHASING POWER

A Strange New Material That's Super-Strong and Super-Light

Nanostructured ceramics could be used to build better airplanes and batteries.

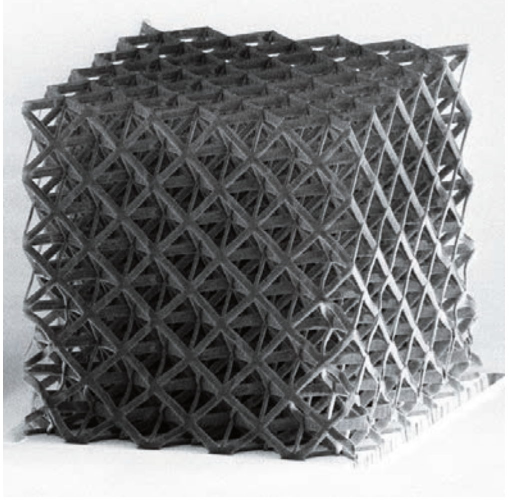
By Katherine Bourzac

A new type of material, made up of nanoscale struts crisscrossed as if in a tiny Eiffel Tower, is one of the strongest and lightest substances ever made. If researchers can figure out how to make the stuff in large quantities, it could be used as a structural material for building planes and cars, or as an improved battery electrode.

In conventional materials, strength, weight, and density are correlated. Ceramics, for example, are strong but also heavy, so they can't be used as structural materials where weight is critical—for example, in the bodies of cars. And when ceramics fail, they tend to fail catastrophically, shattering like glass.

Researchers led by Caltech materials scientist Julia Greer found that by carefully designing nanoscale struts and joints, it is possible to make materials that are not only very strong but light enough to float through the air like a feather. What's more, the method can make ceramics, metals, and other materials that can recover after being crushed, like a sponge. Details of the research were published in the journal *Science*.

At the nanoscale, it turns out, the usual strength-weight-density rules do not apply to materials. In this size range, the structural and mechanical properties of ceramics become less tied to properties such as weight, and they can be altered more precisely. "For ceramics, smaller is tougher," says Greer, who was named one of *MIT Technology Review*'s 35 Innovators Under 35 in 2008 for her work on nanoscale mechanics. This means that nanoscale trusses made from ceramic materials can be both extremely light—unsurprising, since they are mostly air—and very strong.



COURTESY OF JULIA GREER

An electron microscope image shows the material's ceramic nano-lattices.

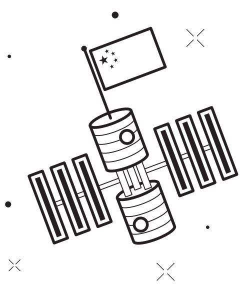
In 2011, researchers at HRL Laboratories, a private engineering research company, created one of the lightest materials ever made, a microlattice of hollow metal tubes. Greer worked with the company to characterize the material, and later she chose to take on the greater challenge of making ceramics with similar properties. This required fine-tuning structures at the nanoscale, meaning the materials are much more difficult to produce.

To make the ceramic nano-trusses, Greer's lab uses a technique called two-photon interference lithography. It's akin to the activity of a very low-yield 3-D laser printer. This method is used to create the desired structure, a lattice, out of a polymer. The polymer lattice is then coated with a ceramic such as alumina. Oxygen plasma etches out the polymer, leaving behind a lattice of hollow ceramic tubes.

Greer's lab showed that by changing the thickness of the tube walls, it's possible to control how the material fails. When the walls are thick, the ceramic shatters under pressure as expected. But trusses with thinner walls, just 10 nanometers thick, buckle when compressed and then recover their shape. "You don't expect these materials to recover—you expect them to be brittle and to fracture," says Christopher Spadaccini, an engineer who specializes in materials manufacturing at the U.S. Department of Energy's Lawrence Livermore National Laboratory in California.

The new materials might be particularly interesting for use in batteries, notes Nicholas Fang, a mechanical engineer at MIT who is also working on nanostructured ceramics. Nanostructures have a very high surface area and are lightweight, a combination that could make for a fast-charging battery that stores a lot of energy in a convenient package. Some companies are already interested in materials with such properties. Greer says she is collaborating with the German company Bosch to apply her designs to lithium-air batteries.

Upfront



2022

The year the Chinese Space Agency expects to complete its first orbital space station.

How to Break Cryptography with Your Bare Hands

The latest way to snoop on a computer is by measuring subtle changes in electrical potential as data is decrypted.

By David Talbot

With enough technical savvy, simply touching a laptop can suffice to extract the cryptographic keys used to secure data stored on it.

The trick is based on the fact that the "ground" electrical potential in many computers fluctuates according to the computation that is being performed by its processor—including the computations that take place when cryptographic software operates to decrypt data using a secret key. Measuring the electrical potential leaked to your skin when you touch the metal chassis of such laptops, and analyzing that signal using sophisticated software, can be enough to determine the keys stored within, says Eran Tromer, a computer security expert at Tel Aviv University.

This remarkable result was described in a paper presented at a conference in South Korea and demonstrated at a cryptography conference in Santa Barbara, California, in August.

A signal can be picked up by touching exposed metal on a computer's chassis with a plain wire. Or that wire can make contact anywhere on the body of an attacker who is touching the computer with a bare hand (sweaty hands work best).

There may be many more undiscovered hardware-related "side channel" attacks, experts say.

The ground signal can also be measured by fastening an alligator clip at the far end of an Ethernet, VGA, or USB cable attached to the computer, or even measured wirelessly with sensitive voltage-detection equipment. The catch is that contact must be made as data is unlocked with a key—during decryption of a folder or an e-mail message, for instance.

Tromer says his research team has used all those methods to extract encryption keys based on widely used high-security standards—4,096-bit RSA keys and 3,072-bit ElGamal keys.

The work contributes to a growing body of evidence that regardless of the software protections people place on computers, there are indirect ways to extract data—so-called "side channel" attacks.

Previous research efforts have found, for example, that analyzing the power consumption of a computer can reveal cryptographic keys. The good news is that analyzing subtle trends in power usage can also reveal whether a computer is being attacked.

"Overall, there are likely tens of undiscovered hardware-related side channels—and we are likely going to hear more from these authors and others," says Radu Sion, a computer security expert at Stony Brook University, in New York.

Tromer says he doesn't know of anybody performing a ground-potential attack to steal real data, but he has notified makers of cryptography software. It is possible to avoid such attacks by adding random data to computations. The developers of a popular free cryptographic software package, GnuPG, incorporated such a patch into the latest version of the software.

TO MARKET

Mobile Reality

Samsung Gear VR

COMPANY:
Samsung

PRICE:
$199

AVAILABILITY:
October 2014

A headset from Samsung will offer a remarkably simple and cost-effective way to experience virtual reality. The device consists of a comfy frame and a set of lenses; the display, graphics, and computer power required to render a vivid virtual world are supplied by a smartphone that slots into the front, running software from Oculus VR, a startup bought earlier this year by Facebook. Though it's lower in resolution and less responsive than some headsets, the cost and form factor could encourage more people to give virtual reality a try.

COURTESY OF SAMSUNG

TOMI UM

Meet the Man Who Really Built Bitcoin

Who cares about Satoshi Nakamoto? Someone else made Bitcoin what it is and has the most power over its destiny.

By Tom Simonite

In March, a bewildered retired man faced journalists yelling questions about virtual currency outside his suburban home in Temple City, California. Dorian Nakamoto, 64, had been identified by *Newsweek* as the person who masterminded Bitcoin—a story that, like previous attempts to unmask its pseudonymous inventor, Satoshi Nakamoto, was soon discredited. Meanwhile, the person arguably most responsible for enabling the currency to swell in value to $7.7 billion, and with the most influence on its future, was hiding in plain sight on the other side of the country, in Amherst, Massachusetts.

That person is Gavin Andresen, a mild-mannered 48-year-old picked as a successor by the real Satoshi Nakamoto, whoever he or she is, in late 2010. Andresen became “core maintainer”—chief developer—of the open-source code that defines the rules of Bitcoin and provides the software needed to make use of it. The combination of Nakamoto’s blessing and Andresen’s years of diligent, full-time work on the Bitcoin code has given him significant clout in Bitcoin circles and stature beyond. The CIA and Washington regulators have looked to him to explain the currency. And it was Andresen who conceived of the nonprofit Bitcoin Foundation, established in 2013, which is the closest thing to a central authority in the world of Bitcoin.

Some Bitcoin enthusiasts offer bombastic predictions that with the low-cost transactions made possible by the stateless virtual currency, Americans will shake off the shackles of the Federal Reserve and poor nations will rise to prosperity. Other Bitcoin boosters have the air of salesmen chasing a mark, reeling off reasons you should buy into the currency in a way that makes you feel you’re not getting the whole story. In contrast, Andresen seems to be in search of quiet personal satisfac-

Upfront

tion, cheerfully calling himself a "geek interested in nuts-and-bolts things."

Still, Andresen has had and maintains more influence than anyone else on the code that determines how Bitcoin operates—and ultimately whether it can survive. The way Andresen wields his power will shape not only Bitcoin's fate but also the prospects for other virtual currencies. Bitcoin's origins may be shrouded in mystery, but plenty is known about Andresen and his past. Formerly known as Gavin Bell, he has been a software engineer ever since he graduated in computer science from Princeton in 1988 and took a job with Silicon Graphics. He worked there for seven years, and then at a series of startups building products from 3-D drawing software to online games for blind and sighted people to play together. Then he encountered Bitcoin in 2010.

Andresen will shape not only Bitcoin's fate but also the prospects for other virtual currencies.

Bitcoins were essentially worthless at the time and extremely tricky to get hold of and use. But Andresen saw technical elegance in Nakamoto's design, and a currency outside the control of any government appealed to what he calls his "mostly libertarian" politics. Rather than being created by a central bank, bitcoins are "mined" by people running software that races to solve a mathematical puzzle. Newly minted bitcoins are the prize, but the mining process, which also serves to verify transactions, is designed to gradually pay out less and less over time until 21 million bitcoins exist.

Eager to see people start using Bitcoin, in 2010 Andresen launched a website called the Bitcoin Faucet, which handed out five free bitcoins to every visitor. (A bitcoin was worth only cents at the time, but each one trades for $600 today; Andresen reduced the size of the handout as bitcoins rose in value, and then shut the site down in 2012.) He also began sending code tweaks and improvements to Nakamoto. Bitcoin's founder liked his work and soon made his protégé's e-mail address the only one on the project's homepage. Andresen formally stepped forward in a December 2010 post on the Bitcoin forum. He has worked full time on the currency ever since. The Bitcoin Foundation paid him $209,648—in bitcoins—in 2013.

His smooth ascent has led to frequent accusations that Andresen is Nakamoto and shed the pseudonym once the currency gained traction. He always flatly denies it. "I am not Satoshi Nakamoto; I have never met him; I have had many e-mail conversations with him," he said after giving a talk in April. "Nobody knows who he is, I think." If that was a lie, Andresen is a remarkable con man. Throughout hundreds of forum posts, e-mail messages, and lines of code, his style has been distinct from that of Nakamoto. It's not known how many bitcoins Andresen holds, but he has said that the return on the bitcoins he accumulated in the currency's early days has been big enough to comfortably retire on.

When Andresen took over from Satoshi Nakamoto in 2010, he laid out the way the project would operate, drawing on his experience managing teams to build software products. A group of five core developers emerged, with Andresen the most senior. Only they had the power to change the code behind Bitcoin and incorporate proposals from other volun-

QUOTED

"I would love for my glasses to give me a little quiet indication about my breathing so I can adjust it."

– Rosalind Picard, MIT Media Lab researcher whose team modified Google Glass to measure the wearer's stress level.

TO MARKET

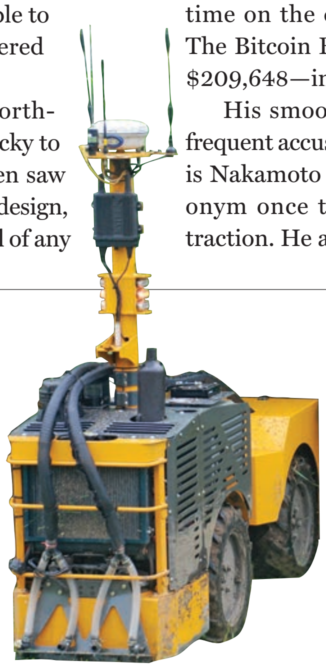
Farm Hand

Rowbot

COMPANY:
Rowbot

PRICE:
$10 per acre

AVAILABILITY:
Now



This summer a Minnesota startup began deploying an autonomous robot that rolls from corn plant to corn plant spraying crop fertilizer. The robot sprays the rows on either side as it travels between them, using GPS to know when it's reached the end of the field and lidar to make sure it stays between rows of mature cornstalks without hitting them. Although such fields could also be fertilized at any time via irrigation, only about 15 percent of U.S. cornfields are irrigated. Mike Schmitt, a professor in the Department of Soil, Water, and Climate at the University of Minnesota, says the robot is "a great additional tool to put in the nutrient management technology toolkit."

COURTESY OF ROSALIND PICARD | DAVID SELLA
COURTESY OF ROWBOT

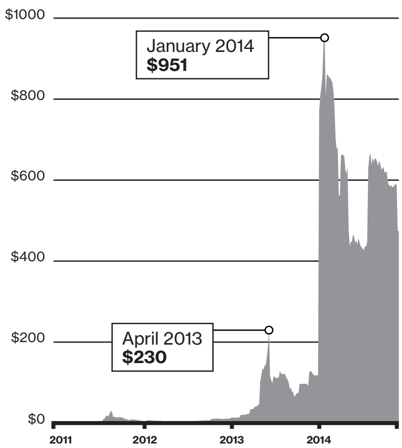
teers. While the price of bitcoins soared over the years, Andresen and the other core developers toiled to improve the software that made it all possible. They fixed security bugs, made the software less prone to crashes, and spruced up the interface to make it easier to use.

That was no small task, because what Nakamoto had left was not the kind of software you would hope to build a product on, let alone an economy, says Mike Hearn, a former Google software engineer who has contributed code to the project. "He released Bitcoin to prove his ideas would work," Hearn says. "It wasn't written to be a long-term sustainable product." Most of the work to turn it into one was done by Andresen and Wladimir van der Laan, the Amsterdam-based coder who took over from Andresen as core maintainer in April, says Hearn. (Van der Laan didn't respond to an interview request.) As bugs were fixed, messy code tidied up, and new features added, most of what Nakamoto wrote disappeared. Less than one-third of Nakamoto's code remains. "He was a brilliant coder, but it was quirky," says Andresen.

The number of people working on the code remains small, but the software behind Bitcoin has never been more critical. As the currency's worth has grown to nearly $8 billion, its constituency has widened from the early libertarian enthusiasts to include investors on Wall Street and in Silicon Valley. U.S. lawmakers and regulators have spoken positively about Bitcoin and made efforts to regulate it.

The risk of security flaws is a constant worry for Andresen. He laughs when he recounts how in 2010 someone tipped off Nakamoto about a bug that made it possible to spend anyone else's bitcoins. "Satoshi just changed the code and told everybody, 'Run this new code—I'm not going to tell you why,'" Andresen says. But although most bugs that turn up in the software today are minor, similar problems could still lurk. "It's why I say Bitcoin is an experiment and you shouldn't invest your life's savings," he says. Unfortunately, the best defense against security flaws—having people review other people's code—is hard to deploy for Bitcoin. Unpaid volunteers prefer to write their own code rather than laboriously read other people's. The currency's value

Value of one bitcoin



SOURCE: COINDESK

is built almost entirely on speculation, so any indication that the system is less than bulletproof can cause a major price shock.

Meanwhile, Andresen must also wrestle with a serious problem in Nakamoto's design. The Bitcoin network is incapable of processing more than seven transactions a second, a tiny volume for a technology with global ambitions. (Only about one Bitcoin transaction is made per second today.) Visa processes almost 480 transactions a second worldwide and can handle up to 47,000 a second.

"I'm worried about it, and there's a big debate in the Bitcoin community about how we are going to do this," says Andresen. His favored solution is to increase the size of the "blocks" of transactions that get confirmed by the network of bitcoin miners every 10 minutes. Not everyone agrees with this proposed fix. Some opponents argue that it would make Bitcoin more centralized. Andresen underlines his own position using the Bitcoin version of Scripture: "If you read Satoshi's writings, it's obvious he intended it as a day-to-day transaction network for everybody," he says.

One way or another, whatever Andresen decides on will probably get done. But he promises that he and the core developers will always listen to other opinions before they make any change to Bitcoin's code. "It really is a consensus-driven process," he says. And he points out that because that code is open source, any dissenters can use it to create a version with their preferred design. But other developers and users have little incentive to threaten the status quo and Andresen's role in it. The value of any currency ultimately rests on a collective belief. In the case of Bitcoin, that faith rests not just in Nakamoto's code but in the people who tend to it.

Andresen has an alternative explanation for why there won't be big changes in the way Bitcoin works. After the transaction issue is resolved, the work of looking after its code will be a job for caretakers, not master builders, he says. Andresen anticipates spending less and less time keeping the currency working, and more in his Amherst home office pondering theories about the economics of virtual currencies and reading the growing academic literature on Bitcoin. "I'm very optimistic going forward," he says. "I hope in 10 years that Bitcoin is really boring."

The software behind Bitcoin has never been more crucial.

Q+A

Peter Thiel

Peter Thiel has been behind some prominent technologies: he cofounded PayPal and was an early investor in such companies as Facebook and LinkedIn. But he's convinced that technological progress has been stagnant for decades. According to Thiel, developments in computers and the Internet haven't significantly improved our quality of life. In a new book, he warns entrepreneurs that conventional business wisdom is preventing them and society as a whole from making major advances in energy, health, and other areas where technology could make the world a better place—though he doesn't offer detailed answers about how we might unlock such breakthroughs. (For a review of the book, see page 81.) Thiel spoke to *MIT Technology Review*'s San Francisco bureau chief, Tom Simonite, at the offices of his venture capital firm, Founders Fund.

You claim that we haven't had significant technological progress since around 1970. What about computing?

Progress in computers and the Internet helps with communications, and it's enabled us to make things far more efficient. On the other hand, most other fields of engineering have been bad things to go into since the 1970s: nuclear engineering, aero- and astronautical engineering, chemical engineering, mechanical engineering, even electrical engineering. We are living in a material world, so that's pretty big to miss out on. I don't think we're living in an incredibly fast technological age.

The Founders Fund's slogan takes a swipe at Twitter: "We wanted flying cars; instead we got 140 characters." Haven't things like iPhones and online social networks improved our quality of life?

Some. Just not enough. That line is not meant to be a critique of Twitter as a business. I think the company will eventually become profitable; the 2,000 people who work there will be gainfully employed for decades to come. But its specific success may be symptomatic of a general failure. Even though it improves our lives in certain ways, it is not enough to take our civilization to the next level.

What kinds of technologies might do that?

There are all these areas where there could be enormous innovation. We could be finding cures to cancer or Alzheimer's. I'm quite interested in enabling people to live much longer. There's an information technology approach, where we optimize your nutrition and give instant feedback using mobile device technology. But I suspect that there are entire new classes of drugs or processes that could rejuvenate body parts. I also think that tenfold improvements might be possible in nuclear power. There are miniaturization technologies where you have much smaller containment structures, and technologies for disposing of and reprocessing fuel that have been underexplored.

What are you doing to create this kind of technology?

Well, we invested in SpaceX [the private rocket company that has taken over some launches for NASA] in 2008 after the first rockets had blown up. The next one did work. We invested in a few biotech companies, and we've been looking at medical devices. These sectors where it's a multiyear commitment are wildly out of fashion among investors. At the same time, I do think that there will continue to be innovation in information technology in the decades ahead. About two-thirds of our work is there.

What companies would you say are taking on big problems?

Tesla is a really interesting example. Most of the components didn't involve really great breakthroughs, but there was this ability to combine them. I think we're generally too drawn to incremental point solutions and very scared of complex operational problems like that.

The paradigmatic example for a large company is Google. Within large companies, you often run into internal bureaucracy and the need to meet the quarterly results cycle. Google has done much less of that than other large companies. It looks like they're making good progress

ANDREAS LASZLO KONRATH

"You have to think of companies like Microsoft or Oracle or Hewlett-Packard as fundamentally bets against technology ... All these companies that start as technological companies become antitechnological in character."

on the self-driving cars, which would be very revolutionary if it happened.

Instead of pursuing major breakthroughs, Silicon Valley is dominated by the philosophy of the "lean startup," which says you have to start small and beat existing products as cheaply as possible.

Great companies had a fairly inspiring long-term vision at their core. It's not the way most of the startups in Silicon Valley think of themselves, but I would say it's the way the really valuable ones do. Apple was not exactly a lean startup when it launched the original Apple computer. If you think that you can't take any bold steps, then you will take only incremental ones. This is why Elon [Musk, founder and CEO of Tesla and SpaceX] is so inspiring. Tesla and SpaceX both represented fairly big quantum leaps.

Can technology companies that start out bold stay that way when they become established? Many large computing companies get cautious.

You have to think of companies like Microsoft or Oracle or Hewlett-Packard as fundamentally bets against technology. They keep throwing off profits as long as nothing changes. Microsoft was a technology company in the '80s and '90s; in this decade you invest because you're betting on the world not changing. Pharma companies are bets against innovation because they're mostly just figuring out ways to extend the lifetime of patents and block small companies.

All these companies that start as technological companies become antitechnological in character. Whether the world changes or not might vary from company to company, but if it turns out that these antitechnology companies are going to be good investments, that's quite bad for our society.

You hold up the Apollo program, the freeway system, and the Manhattan Project as examples of big leaps that we need in technology. But those were all government projects. Should the U.S. government return to funding such things?

There is an argument that there should be state funding to help things get started where there are not many profits that could be captured. It's in the public interest. But the way the U.S. government today is dominated by lawyers rather than scientists or engineers suggests that it is very poorly suited for evaluating these kinds of projects.

For example, you probably could not restart nuclear power in the U.S. without the role of government. But because our government does not believe in complex coördination and planning, it will not restart the nuclear industry. It's quite possible it will just not get restarted.

Might one of the newer economies, such as China, retain that belief in big goals?

I think China's medium-term future will involve simply copying things that worked in the developed world—what I call globalization. That's the rational choice. It's how we develop the developing world. The question we don't ask enough is, how do we develop the developed world? It's through the push for technology.

The economist Robert Gordon says that economic growth and technological progress are stalled because new technology won't deliver as many gains as the Industrial Revolution did. Do you share that view?

I agree with both Robert Gordon on the one hand and Ray Kurzweil [futurist author turned Google executive] on the other. I'm not as pessimistic as Gordon, because I do see a lot of progress in the information technology sector, but I'm not nearly as optimistic as Kurzweil. His book *The Singularity Is Near* gives a sense that it's just this force of nature that's coming, whereas I think we make a cultural decision to develop technologies.

The way some pessimists put it is that all the low-hanging fruit has been picked. I would argue that there was never any low-hanging fruit; it was always of intermediate height and the question was, were people reaching for it or not? I'm frustrated because I think technology is progressing slowly, but I'm optimistic because I think it could be going a lot better.

The Right Way to Fix the Internet

Letting go of an obsession with net neutrality could free technologists to make online services even better.

By George Anders

If you're like most people, your monthly smartphone bill is steep enough to make you shudder. As consumers' appetite for connectivity keeps growing, the price of wireless service in the United States tops $130 a month in many households.

Two years ago Mung Chiang, a professor of electrical engineering at Princeton, believed he could give customers more control. One simple adjustment would clear the way for lots of mobile-phone users to get as much data as they already did, and in some cases even more, on cheaper terms. Carriers could win, too, by nudging customers to reduce peak-period traffic, making some costly network upgrades unnecessary. "We thought we could increase the benefits for everyone," Chiang recalls.

Chiang's plan called for the wireless industry to offer its customers the same types of variable pricing that have brought new efficiencies to transportation and utilities. Rates increase during peak periods, when congestion is at its worst; they decrease during slack periods. In the pre-smartphone era, it would have been impossible to advise users ahead of time about a zig or zag in their connectivity charges. Now, it would be straightforward to vary the price of online access depending on congestion and build an app that let bargain hunters shift their activities to cheaper periods, even on a minute-by-minute basis. When prices were high, consumers could put off non-urgent tasks like downloading Facebook posts to read later. Careful users could save a lot of money.

Excited about the prospects, Chiang patented his key concepts. He dubbed his new service GreenByte and formed a company, now known as DataMi, to build the neces-

Illustration by Matt Dorfman

The Internet has progressed because net neutrality has been one of many objectives that can be balanced against one another. If neutrality becomes completely inviolable, it's a different story.

sary software. Venture capitalists and angel investors put more than $6 million into the company. A seasoned wireless executive, Harjot Saluja, signed on to be the chief executive, while prominent people such as Reed Hundt, a former chairman of the Federal Communications Commission, joined DataMi's advisory board. Everything seemed aligned for Chiang and Saluja as they set out to make "smart data pricing" a reality.

Today, GreenByte has vanished from sight. Nobody on DataMi's team is working on the project anymore. The startup has regrouped in favor of two other services, including one that helps businesses calculate how much of their employees' cell-phone bills should be reimbursed because of work-related usage. The reasons for the switch have nothing to do with GreenByte's technical ability to make good on its promise. In early user tests, smart data pricing delivered everything that DataMi's patents predicted.

But politics got in the way.

A huge debate has erupted about the degree to which Internet carriers should be subject to a concept known as net neutrality. In its simplest form, the idea is that Internet service providers such as AT&T, Comcast, and Verizon shouldn't offer preferential treatment to certain types of content. Instead, they should send everything to their customers with their "best efforts"—as fast as they can manage. Nobody can pay your ISP for a "fast lane" to your house. Carriers can't show favoritism toward any of their own services or applications. And nobody providing lawful content can be slowed or blocked.

At this point, net neutrality is only a principle and not a law. Though the FCC put an ambiguously worded version on the books in 2010, it was struck down this year by a federal district court. But now, as the FCC is deliberating how to redo the policy, it's facing passionate demands to restore and possibly even tighten the rules, giving ISPs even less leeway to engage in what regulators have typically called "reasonable network management."

Until about a year ago, Chiang and his colleagues thought their data-pricing idea had so much common-sense appeal that no one would regard it as an assault on net neutrality—even though it would let carriers charge people more for constant access. But then, as the debate heated up, everything got trickier. Ardent defenders of net neutrality began painting ever darker pictures of how the Internet could suffer if anyone treated anyone's traffic differently. Even though Chiang and Saluja saw variable pricing as pro-consumer, they had no lobbyists or legal team and decided they couldn't afford a drawn-out battle to establish that they weren't on the wrong side.

For network engineers, DataMi's about-face isn't an isolated example. They fear that overly strict net neutrality rules could limit their ability to reconfigure the Internet so it can handle rapidly growing traffic loads.

Dipankar Raychaudhuri, who studies telecom issues as a professor of electrical and computer engineering at Rutgers University, points out that the Internet never has been entirely neutral. Wireless networks, for example, have been built for many years with features that help identify users whose weak connections are impairing the network with slow traffic and incessant requests for dropped packets to be resent. Carriers' technology assures that such users' access is rapidly constrained, so that one person's bad connection doesn't create a traffic jam for everyone. In such situations, strict adherence to net neutrality goes by the wayside: one user's experience is degraded so that hundreds of others don't suffer. As Raychaudhuri sees it, the Internet has been able to progress because net neutrality has been treated as one of many objectives that

Protesters rallied at the Federal Communications Commission in May as the agency considered new Internet rules.

ALEX WONG/GETTY IMAGES

can be balanced against one another. If net neutrality becomes completely inviolable, it's a different story. Inventors' hands are tied. Other types of progress become harder.

Rather than debate such subtleties, net neutrality's loudest boosters have been staging a series of simplistic—but highly entertaining—skits in an effort to rally the public to their side. In September, popular websites such as Reddit and Kickstarter simulated page-loading debacles as a way of getting visitors to believe that if net neutrality isn't enacted, the Internet could slow to a crawl. That argument has been picked up by TV comedians such as Jimmy Kimmel, who showed a track meet in which the best sprinters represented cable companies with their own fast lanes. A stumbling buffoon in his underwear portrayed the shabby delivery standards that everyone else would endure.

Even President Barack Obama has been publicly reminding regulators of his commitment to net neutrality. In August he declared, "You don't want to start getting a differentiation in how accessible the Internet is to different users. You want to leave it open so the next Google and the next Facebook can succeed."

Clearly, most Americans aren't happy with their Internet service. It costs more to get online in the United States than just about anywhere else in the developed world, according to a 2013 survey by the New America Foundation. In fact, U.S. service is sometimes twice as expensive as what's available in Europe—and slower, too. Meanwhile, the University of Michigan found in a recent public survey that U.S. Internet service providers rank dead last in customer satisfaction scores against 42 other industries. Specific failings range from unreliable service to dismal call-center performance.

With lots of U.S. consumers wanting the government to do something about Internet service, strengthening net neutrality feels like a way to do it. Given that most Internet providers are urging the FCC to let this principle disappear from the books, it's natural to call for the opposite approach. Yet that would probably be the wrong move. It's possible to overdose on something even as benign-sounding as neutrality.

Key Events in Net Neutrality

2002 Tim Wu, then a law professor at the University of Virginia, introduces the term.

2005 A small ISP based in North Carolina is fined $15,000 for blocking its customers from using voice-over-Internet services.

2006 Several bills that would enshrine net neutrality in law are introduced; none will pass.

2008 The FCC sanctions Comcast, the largest U.S. ISP, for slowing its customers' connections to the download service BitTorrent.

2010 A federal appeals court says the FCC overstepped its authority in the Comcast ruling. In response, the agency issues an "Open Internet" order in hopes of affirming principles of net neutrality.

2014 Circuit court overturns the Open Internet order on the grounds that the FCC was improperly regulating broadband as both an "information service" and a "telecommunications service."

Bitstreams

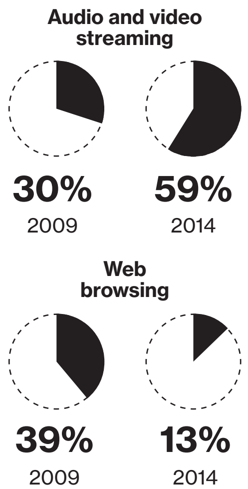
The two sides in the net neutrality debate sometimes seem to speak two different languages, rooted in two different ways of seeing the Internet. Their contrasting perspectives reflect the fact that the Internet arose in an ad hoc fashion; there is no Internet constitution to cite.

Nonetheless, many legal scholars like to point to their equivalent of the Federalist Papers: a 1981 article by computer scientists Jerome Saltzer, David Reed, and David Clark. The authors' ambitions for that paper ("End-to-End Arguments in System Design") had been modest: to lay out technical reasons why tasks such as error correction should be performed at the edges, or end points, of the network—where the users are—rather than at the core. In other words, ISPs should operate "dumb pipes" that merely pass traffic along. This paper took on a remarkable second life as the Internet grew. In his 2000 book *Code*, a discussion of how to regulate the Internet, Harvard law professor Lawrence Lessig said the lack of centralized control embodied in the 1981 end-to-end principle was "one of the most important reasons that the Internet produced the innovation and growth that it has enjoyed."

Tim Wu built on that idea in a 2002 article published when he was a law professor at the University of Virginia. In that and subsequent papers, he wrote that the end-to-end principle stimulated innovation because it made possible "a Darwinian competition among every conceivable use of the Internet so that only the best survive." To promote

Changes in Internet Habits

Content that is sensitive to delays now accounts for a majority of Internet usage.



SOURCE: SANDVINE

that competition, he said, "network neutrality" would be necessary to eliminate bias for or against any particular application.

Wu acknowledged that this was a new concept, with "unavoidable vagueness" about the dividing line between allowable network-management decisions and impermissible bias. But he expressed hope that others would refine his idea and make it more precise.

That never happened. The line remains as blurry as ever, which is one reason the debate over net neutrality is so intense.

Barbara van Schewick, a leading Internet scholar at Stanford and a former member of Lessig's research team, expresses concern that if profit-hungry companies are left unfettered to choose how to handle various types of traffic, they "will continue to change the internal structure of the Internet in ways that are good for them, but not necessarily for the rest of us." She warns of the perils of letting Internet providers promote their own versions of popular services (such as Internet messaging or Internet telephony) while degrading or blocking customers' ability to use independent services (such as WhatsApp in messaging or Skype in telephony). Such practices have occasionally popped up in Germany and other European markets, but they have rarely been seen in the United States, a disparity that van Schewick credits to the FCC's explicit or implicit commitments to net neutrality.

Internet service providers such as AT&T have publicly insisted that they wouldn't ever rig their networks to promote their own applications, because such obvious favoritism would cause customers to cancel service en masse. Skeptics counter that in many locales, consumers have little choice but to stick with their current broadband provider, because there is barely any competition.

Van Schewick also argues that it would be a mistake to let the likes of AT&T or Comcast charge independent content and service creators (including Internet telephony providers such as Skype or Vonage) to secure the best possible access to end users. Though such access fees exist in other industries—cereal and toothpaste companies, for example, pay "slotting fees" to major grocers in order to get optimal shelf space in stores—van Schewick warns that charging such fees to online companies would "make it more difficult for entrepreneurs to get outside funding." In other recent writings, she has said it would be ill-advised to let carriers decide without input from customers whether to optimize different versions of their services for different types of traffic, such as video versus speech and text.

But while van Schewick and other advocates are trying to promote an "open Internet," codifying too many overarching principles for the Internet makes many engineers uncomfortable. In their view, the network is a constant work in progress, requiring endless pragmatism. Its backbone is constantly being torn apart and rebuilt. The best means of connecting various networks with one another are always in flux.

"You can't change congestion by passing net neutrality or doing that kind of thing," says Tom Leighton, cofounder and chief executive of Akamai Technologies. His company has been speeding Internet traffic since the late 1990s, chiefly by providing more than 150,000 servers around the world that make it possible for content creators to store their most-demanded material as close to their various users as possible. It's the kind of advance in network management that helped the Internet survive the huge increases in traffic over the last two decades. To keep traffic humming online, Leighton says, "you're going to need technology."

If some people want their Internet connections to deliver ultrahigh-resolution movies, they might be better served by flexible arrangements that eschew strict equity for all bits and instead prioritize video.

A central tenet of net neutrality is that "best efforts" should be applied equally when transmitting every packet moving through the Internet, regardless of who the sender,

recipient, or carriers might be. But that principle merely freezes the setup of the Internet as it existed nearly a quarter-century ago, says Michael Katz, an economist at the University of California, Berkeley, who has worked for the FCC and consulted for Verizon. "You can say that every bit is a bit," Katz adds, "but every bitstream isn't the same bitstream." Video and voice transmissions are highly vulnerable to errors, delays, and packet loss. Data transmissions can survive rougher handling. If some consumers want their Internet connections to deliver ultrahigh-resolution movies with perfect fidelity, those people would be better served, Katz argues, by more flexible arrangements that might indeed prioritize video. Efficiency might be more desirable than a strict adherence to equity for all bits.

House of Cards

About a year ago, Netflix's customers noticed something disquieting when they tried to stream popular shows such as *House of Cards*. Their download speeds became annoyingly slow and some shows wouldn't load at all, regardless of whether these customers relied on Time Warner Cable, Verizon, AT&T, or Comcast. Network congestion had taken hold—with transmission speeds dropping as much as 30 percent, according to Netflix's own data. Last March, Netflix's CEO, Reed Hastings, lashed out at the major U.S. Internet service providers, accusing them of constraining Netflix's performance and pressuring his company to pay big interconnection fees.

Over the next few months, Netflix and its allies portrayed this slowdown as an example of cable companies' most selfish behavior. In communications with the FCC, Netflix called for a "strong version" of net neutrality that would block the companies from charging fees to online service providers. In his blog, Hastings declared that net neutrality must be "defended and strengthened ... to ensure the Internet remains humanity's most important platform for progress."

But the situation isn't as black-and-white as Hastings's indignant posts suggested.

For many years, high-volume sites run by Facebook, YouTube, Apple, and the like have been negotiating arrangements with many companies that ferry data to your Internet service provider—backbone operators, transit providers, and content delivery networks—to ensure that the most popular content is distributed as smoothly as possible. Often, this means paying a company such as Akamai to stash copies of highly in-demand content on multiple servers all over the world, so that a stampede for World Cup highlights creates as little strain as possible on the overall Internet.

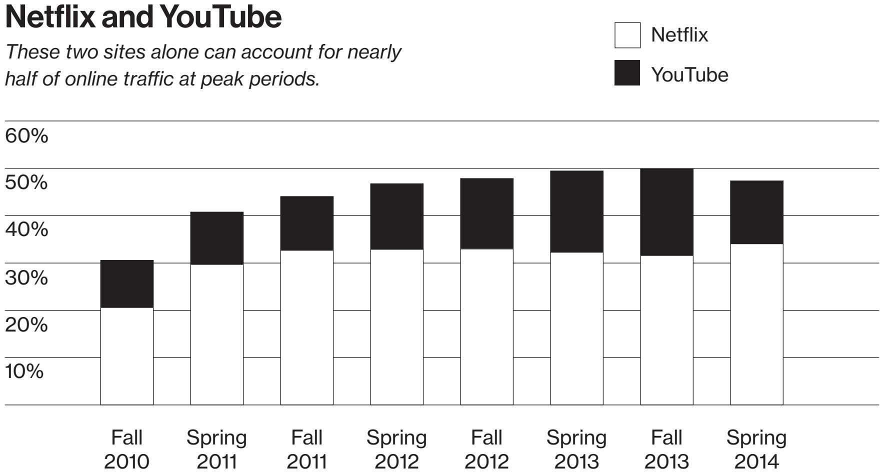
There's no standard way that these distribution arrangements are negotiated. Sometimes no money changes hands. In other situations, content companies pay for distribution. In theory, distribution companies could pay for content. In Netflix's case, as demand has skyrocketed for its movies and TV shows, the company has negotiated a wide range of ways to help route its content around the Internet as efficiently as possible.

As Ars Technica reported earlier this year, Netflix started to realign its distribution methods in mid-2013. As its traffic soared, that created greater demands on all the Internet service providers that needed to handle *House of Cards* and its kin. By some estimates, Netflix last year was accounting for as much as one-third of all U.S. Internet traffic on Friday evenings. One of Netflix's distribution allies (Level 3) restructured its terms with Comcast, reflecting the expenses associated with extra network connections, known as peering points, that Comcast needed to install in order to handle this rising traffic. Another (Cogent Communications) balked at the idea of defraying Comcast's costs, and as a result, additional connections from Cogent to Comcast weren't installed.

The result: Netflix's videos began to stutter. In the short term, Netflix resolved the problem by paying for more of the peering points that carriers such as Comcast and Verizon required. More strategically, Netflix is arranging to put its servers in Internet service providers' facilities, providing them with easier access to its content.

Netflix and YouTube

These two sites alone can account for nearly half of online traffic at peak periods.



Much of the lobbying in favor of net neutrality is coming from large, publicly traded companies that make momentary allusions to the well-being of garage-type startups.

In the long run, carriers and content companies are likely to keep tussling about the ways they connect—simply because these are the sorts of business contracts that must be revisited as circumstances change. That's why Hundt, FCC chairman from 1993 to 1997, says it's a mistake to portray Netflix's scuffle with the carriers as a critical test of the neutrality principle. It's more like a routine business dispute, he says. "This is a battle between the rich and the wealthy," he adds. "Both sides will have to figure out, on their own, how to get along."

Hundt says the Netflix fight shouldn't distract regulators who are trying to figure out the best way to keep the Internet open. They should be focusing, he says, on making sure that everyday customers are getting high-speed Internet as cheaply and reliably as possible, and that small-time publishers of Internet content can distribute their work. It's worth noting that much of the lobbying in favor of net neutrality is coming from large, publicly traded companies that make momentary allusions to the well-being of garage-type startups but are mainly focused on disputes that apply to the Internet's biggest players. A tiny video startup doesn't generate enough volume to force Comcast to install extra peering points.

Zero Rating

In the rest of the world, where net neutrality is not insisted on, innovative approaches to wireless Internet pricing are catching on. At the top of the list is "zero rating," in which consumers are allowed to try certain applications without incurring any bandwidth-usage charges. The app providers usually pay the wireless carriers to offer that access as a way of building up their market share in a hurry.

In much of Africa, people with limited usage plans can enjoy free access to Facebook or Wikipedia this way. In Europe, many music-streaming sites have hammered out arrangements with various wireless carriers in which zero-rating promotions become a major means of marketing. In China and South Korea, subsidized wireless options are springing up too. Such arrangements can help hold down mobile-phone bills and possibly even get people online for the first time.

In the United States, T-Mobile lets customers tap into a half-dozen music sites, such as Pandora and Spotify, without incurring usage charges. And AT&T has been experimenting with zero rating. But overall, things are moving slowly.

Consumers around the globe may find zero rating delightful, but net neutrality champions such as Jeremy Malcolm, senior global policy analyst at the Electronic Frontier Foundation, object on principle because it lets content providers pay carriers for access to consumers. In his view, carriers can't be trusted in any situation that involves special deals for certain services.

When Tim Wu talked about net neutrality a decade ago, he framed it as a way of ensuring maximum competition on the Internet. But in the current debate, that rationale is in danger of being coöpted into a protectionist defense of the status quo. If there's anything the Internet's evolution has taught us, it's that innovation comes rapidly, and in unexpected ways. We need a net neutrality strategy that prevents the big Internet service providers from abusing their power—but still allows them to optimize the Internet for the next wave of innovation and efficiency.

George Anders is a writer based in Northern California. He shared in the 1997 Pulitzer Prize given to the Wall Street Journal *for national reporting.*

China's GMO Stockpile

With its world-leading research investments and vast size, China will dominate the future of genetically modified food—despite the resistance of its population.

By David Talbot

It is a hot, smoggy July weekend in Beijing, and the gates to the Forbidden City are thronged with tens of thousands of sweat-drenched tourists. Few make the trek to the city's east side and its more tranquil China Agricultural Museum, where several formal buildings are set amid sparkling ponds ringed by lotus plants in full pink bloom. The site, which is attached to the Ministry of Agriculture, promises that it will "acquaint visitors with the brilliant agricultural history of China"—but what's missing from the official presentation is as telling as what's on display.

At least 9,000 years ago, people living in China were the first to cultivate rice, developing elaborate irrigation systems. Today, rice is the nation's (and half the world's) most important crop. Some 2,500 years ago, the Chinese also invented the first really efficient iron ploughshares, called *kuan*, with a curved V shape that efficiently turned hard soil. These millennia-old innovations are matched by those of the past century. A display honors Yuan Longping, China's revered "father of hybrid rice," who in the mid-1960s posited that if he could find male-sterile rice plants—ones unable to self-pollinate—he could create hybrid strains reliably

Caixia Gao (right), with wheat researcher Fanyun Lin, leads advanced work on GMOs.

Illustrations by Seth Armstrong

and at large scale. (In general, hybrids are more vigorous and higher-yielding than the parent varieties.) He later found such plants and, together with other researchers, created a process to make high-yielding hybrids year after year, revolutionizing rice production.

But the exhibits don't mention the vast suffering wrought by Chinese agricultural failure. Yuan himself lived through Chairman Mao Zedong's "Great Leap Forward" of 1958–1961, which triggered a collapse in food production and distribution by banning private farming in favor of vast collective farms. As many as 45 million people died, most by starvation. The museum also says nothing about the most fought-over product of modern-day agricultural technology: genetically modified organisms, or GMOs. Yes, there's a 1990s-era gene gun, which used high-pressure gas to blast DNA-coated particles into plant cells to create early transgenic crops. And there's a stalk representing the big GMO success story that used this approach: Bt cotton, a pest-resistant variety that has been planted widely in China for 15 years, greatly increasing production while slashing pesticide use. (The plant, which incorporates DNA from a soil bacterium that's harmful to insects, makes up 90 percent of the cotton crop and by one estimate produces a $1 billion annual economic gain for farmers.) But the story seems to end more than a decade ago.

China's ruling Communist Party faces rising popular opposition to GMOs. As in any other nation, there are a variety of views within China about whether it's safe to eat food made with genetically engineered ingredients. But Chinese citizens have lately witnessed a number of major food safety scandals, including a 2008 disaster in which melamine-tainted milk products killed six babies or toddlers, sending 54,000 more to the hospital, and a 2010 revelation that some cooking oil sold to consumers had been recovered from drains and probably contained carcinogens. Against this backdrop, otherwise implausible-sounding claims from a vocal minority of GMO critics (such as an assertion that GMO soybean oil was associated with a higher incidence of tumors) gain traction in the country's social media, which many Chinese favor over official state media as a source of news. The Chinese press and social media lit up when, in 2012, Greenpeace released a scary-sounding report on a research project that involved feeding children "golden rice," which is engineered to produce beta-carotene and thus make up for vitamin A deficiencies. (It turned out that the parents were not told the rice was genetically modified; China fired three researchers involved.)

Recent informal opinion surveys in Chinese social media suggest that large majorities believe GMOs are harmful, and scientific surveys also indicate that opposition is significant. An academic survey this year found that roughly one-third of respondents opposed GMOs outright and another 39 percent

After the Famine

China helped pioneer rice hybridization, and its government is now the world's top spender on GMO crop research.

1958: China's **Great Leap Forward** bans private food production and creates farming communes—resulting in mass starvation over the next four years.

1973: Agricultural scientist Yuan Longping **creates and reproduces high-yield hybrid rice** in China, dramatically increasing the nation's rice yields.

Mao's "Great Leap Forward" triggered a collapse in food production by banning private farming in favor of vast collective farms. As many as 45 million people died.

1985: China begins establishing **30 national biotech labs**. Today nearly 400 academic or national labs work on plant biotech.

1992: China becomes the **first country to grow a commercial GMO crop**: a virus-resistant tobacco.

1997: Farmers plant transgenic **insect-resistant cotton**.

2008: China becomes a net importer of food. **It is now the world's largest food importer.**

2009: Government issues **five-year safety certificates** for insect-resistant rice and GM corn that's more digestible to pigs—but never allows planting.

2014: Using new gene-editing technologies, Chinese researchers **develop a disease-resistant wheat**.

worried about them—a stark difference from earlier government surveys. Such opposition is often tinged with nationalism. With growing quantities of GM corn and soybeans being imported to China—largely for animal feed but also for processing into food ingredients such as oil—the notion is spreading through social media that Americans are trying to poison Chinese consumers, or at least foisting on them the GMOs that they refuse to eat themselves (although in fact, most processed food Americans eat contains genetically modified ingredients). A Chinese general decreed earlier this year that no GMO ingredients, not even a little oil, should be allowed in soldiers' food. So for now, anyway, the government is holding back on approving new GMOs for food crops. Today no genetically modified food (with the exception of a virus-resistant papaya) is grown in China, even for animal feed. The Ministry of Agriculture issued its last significant safety approvals five years ago—for a pest-resistant rice developed in China and a variety of corn whose phosphorus content is more digestible to pigs, enhancing growth and reducing subsequent pollution—but never gave the okay for actual planting. The safety certificates expired in August. A recent endorsement of GMOs by the aging Yuan Longping himself has done little to move the policy or change public opinion. Ji-kun Huang, director of the Center for Chinese Agricultural Policy, says, "The technology is ready, but politically, it's sensitive. Commercialization will be a long way off. Rice is a staple food, and public concern about safety is serious."

Yet despite the uncertainties, research on GMO crops continues. By one count published in *Nature Biotechnology*, 378 Chinese groups employing thousands of scientists are engaged in this work. The government will have spent some $4 billion on GMOs by 2020. Researchers are using the latest modification technologies and drawing from high-throughput genomic analysis of thousands of crop strains, accelerating the pace of discovery.

Cautious though they are of arousing public opposition, Chinese leaders are well aware that their country will need a lot more food. Growing it will require new agricultural tricks. The world's most populous nation, China has more than 1.3 billion inhabitants, a number expected to rise to almost 1.4 billion by 2030. Meanwhile, accelerating climate change will pose great challenges for farmers, bringing deeper droughts, more flooding, and hotter heat waves (see "Why We Will Need Genetically Modified Foods," January/February 2014). Although crop yields in China tripled from the 1960s through the 1990s, thanks to hybrid varieties and generous spraying of pesticides, those gains slowed significantly 15 years ago. Since then, yields have flattened. To make matters worse, rapid industrialization is eating into the supply of arable land. Finally, the population will be getting not just larger but richer; rising GDP means more demand for meat, putting huge pressure on crops. Demand for imported corn alone is expected to surge from about five million tons this year to more than 20 million tons in just 10 years. Much of that crop is expected to feed animals ultimately headed for Chinese slaughterhouses.

In anticipation, the nation is building a storehouse of genetically modified crop strains for future use. China sees this as a way of protecting its long-term security. In fact, the country is the world's top public spender on genomics and genetic modification of crops, says Scott Rozelle, a China scholar and food security expert at the Freeman Spogli Institute for International Studies at Stanford University. "Certainly we [the United States] aren't doing much—and the big multinationals aren't doing much right now in terms of spending on plant biotech research," Rozelle says. "And yet China continues to do it." So far China has been able to feed itself, so there is no impetus to deploy this new technology, he adds. "Yet they continue to pour money into it. Are they doing it for the love of science? They are putting away for a rainy day—or a non-rainy one. And when that day comes, I think they will have more GM technologies than anyone."

KEYSTONE-FRANCE VIA GETTY IMAGES

The government keeps current food prices low by investing in irrigation and subsidizing farmers, and it keeps meat on the table thanks at least in part to imported corn and soybeans. China became a net food importer in 2008 and the world's top food importer four years later; it now imports about 5 percent of its food. This makes China's stance on GMO food crops critical for the entire global market; if China green-lights GMOs, many other countries that export to China may accept them too.

Meanwhile, the rising use of imports puts pressure on China to do more to feed its own people, and that helps drive internal research on GMOs. Imports are "a very important issue for food security," says Dafang Huang, chief scientist of the Biotech Research Institute at the China Academy of Agricultural Sciences in Beijing, which is collaborating on a vast array of agricultural genome sequencing and GMO efforts. "I think the high-level officials are very concerned. We have to use the new technology. We have to develop the GMO."

Rice Editor

Exuberant and prone to charming bursts of laughter, Caixia Gao embodies the optimistic, energetic present of GMO research in China. Wearing a gray T-shirt emblazoned with "Just Do It" in large pink letters, she leads a tour of her greenhouses at the State Key Lab of Plant Cell and Chromosome Engineering at the Institute of Genetics and Developmental Biology, part of the Chinese Academy of Sciences in Beijing. She's one of the world's leaders in using sophisticated gene-editing technologies, including those known as TALENs and CRISPR. The earlier gene guns were analogous to shotguns: they could not precisely control where they inserted DNA into a plant cell. The process was, quite literally, hit or miss. The new methods, by contrast, insert molecules that can cut specific sequences of DNA. This makes it possible to delete or add a gene at any desired spot on the genome, or even to change just a few nucleotides, something unthinkable with older methods. Since the new tools make their changes without relying on genes taken from other species such soil bacteria, they could also answer some of the objections leveled against transgenic crops.

Large-scale field trials are going on all over the country, but public data is scant. Scientists feel they must hide the locations of the trials. They have reason to worry.

Gao is at the vanguard of genetic engineering in rice. As she strides through a humid greenhouse filled with test trays of rice plants (the air feels cleaner here—though anything would be better than the heavy smog outdoors), she explains that each has had one or more of its genes "knocked out" using the new editing tools. On one shelf sits a strain that grows straighter; more plants can fit in a given area. On another, she shows off one with a desirable fragrance: "It smells good and tastes good—for quality." These features could help the market accept future strains engineered for traits such as disease resistance. Finally, she arrives at a tray of rice plants half as tall as the surrounding ones. Their small stature resulted from editing out a single gene; while the implications aren't yet clear, the hope is that less of the plant's energy is going into making leaves and more into making the edible seeds. That would permit higher yields.

Gao's trays are part of a massive nationwide enterprise. In 2002, Chinese scientists were among the first to sequence a rice genome; this year they released the sequences of 3,000 varieties as part of a continuing effort with the International Rice Research Institute (IRRI) in the Philippines and the Beijing Genomics Institute to develop a crop known as "green super rice" (GSR). BGI has been using high-throughput technology to systematically compare these strains. The goal is to identify the genes that might be important for traits such as yield, flavor, pest and herbicide resistance, and tolerance to drought, salt, and immersion. Combined with the gene-editing tools, this new wealth of knowledge means that an era of very rapid and precise GMO development is at hand.

Gao and colleagues are doing similar systematic studies on the next-most-important crops: corn, wheat, and soybeans. They recently invented a wheat strain that resists the second-most-common wheat disease, powdery mildew. We drove to the outskirts of Beijing, where behind a row of industrial buildings, outdoor test plots were full of new crop varieties made with both conventional breeding and GMO technology. The GMOs included a soybean plant whose beans produce more oil and an acre or so of rice that can avoid leaf death.

Large-scale field trials are going on all over the country, but public data is scant. Two to three hours outside Beijing, a number of test fields of wheat have recently been harvested, Dafang Huang says. Work at the Chinese Academy of Agricultural Science includes planting drought-resistant varieties of wheat. Other Chinese institutions are making similar progress on drought-resistant corn, he adds. But like many of their colleagues across the country, the scientists feel that they must hide the locations of the trials. (They have reason to worry. Three years ago Australian Greenpeace activists destroyed a field of GM wheat plants; last year, activists in the Philippines destroyed a test plot

China's Research Output

Hundreds of state-funded research groups in China are working on GMOs, including these three examples.

Disease-resistant wheat
A wheat with three genes edited out, conferring resistance to the fungal disease called powdery mildew.

Bt rice
A transgenic rice that wards off major insect pests, the leaffolder and yellow stem borer, without reducing yield.

Phytase corn
A transgenic corn that releases phosphorus from phytate molecules, aiding digestion for chicken and pigs.

of golden rice. Gao and Huang told me they worry that something similar could happen in China.) But while there is no central public repository of field trial data, Huang told me it was safe to assume that the plantings are widespread—and productive. "You can imagine that many, many field trials are going on in the different areas," he says. "Basic research is very open, but for the field trials, I think the data is very secret."

Researchers sometimes wonder if their work will ever see the light of day. "We can do research—we have enough financial support—but I don't know if Chinese scientists can produce the product," Gao says. At the National Key Laboratory of Crop Genetic Improvement at Huazhong Agricultural University in Wuhan, Qifa Zhang, the lab's director, is hard at work on GSR. He also developed an insect-resistant Bt rice, which is still barred from commercialization. But he's reticent when it comes to talking about GMOs. "Inaccurate quotations of such interviews have done me more harm than help," he lamented in an e-mail. "I prefer not to talk."

Going It Alone

At the beginning of this year, China released a policy document stressing the need to match its world-class basic research with a more modernized seed industry. The goal: to consolidate many of the country's thousands of seed companies and develop ones more like Monsanto, linking basic research to large-scale production of seed. So I was looking forward to visiting Da Bei Nong Group, the giant Chinese animal feed and seed company that is the most valuable agricultural company in the Chinese market. I was to visit the DBN Biotech Research Center in Beijing, headed by Lu Yuping, former head of Syngenta's research unit there. DBN's projects include herbicide-tolerant soybeans as well as corn with so-called stacked traits of herbicide and insect resistance; the tour was to include a view of extensive laboratory and field trials.

Then came the indictments.

In early July, just three weeks before my visit, a federal grand jury in Des Moines, Iowa, indicted Mo Yun, wife of Da Bei Nong Group's billionaire chairman, on one count of conspiracy to steal trade secrets: to wit, valuable corn seed from test fields in Iowa and Illinois owned by DuPont Pioneer, Monsanto, and LG Seeds. Yun's indictment followed those of six other employees of the company or its subsidiaries in late 2013. One was accused of trying to drive across the border from Vermont to Canada with containers of kernels stashed under the seats; others are accused of packing stolen corn into Ziploc bags and attempting to FedEx them from Illinois to Hong Kong. All told, the cost to Pioneer and Monsanto totaled $500 million, prosecutors allege.

Despite all this, the circumspect, soft-spoken Lu gamely agreed to meet me for an off-site interview. Unsurprisingly, he would not comment on the U.S. indictments, saying the accusations are unrelated to his unit. But he says the DBN Biotech Center is using gene-editing technologies to create male-sterile rice, hoping to accelerate the sort of research Yuan pioneered, while it continues the top-priority research into herbicide tolerance in corn and soybeans. He stressed that the company was working on its own varieties, in part to deal with insect threats that occur mostly in China. "Some pests are China-specific, and this is our challenge—we have to have new innovations," he says.

While the accusations fit into a larger narrative of alleged Chinese corporate espionage, it would be a mistake to assume that such malfeasance, if it's actually occurring, is a mainstay of China's GMO strategy. Stealing seeds would help avoid a couple of years of breeding work. But given the extensive government-funded in-house work it has to

draw upon, DBN's own biotech R&D may be as productive as that of multinational seed companies, says Carl Pray, an economist at Rutgers University who is a close watcher of the Chinese agriculture sector. His sense is that DBN is "doing some pretty good research," he says, adding, "I don't think that the research they are doing really can match the latest research at Monsanto, DuPont, or Syngenta, but the technology is probably getting to a point where it will work fairly well in China."

In addition, Chinese companies would enjoy structural and economic advantages. The example of Bt cotton is instructive. Back in 1997, Monsanto introduced its insect-resistant cotton to China shortly before Biocentury Transgene, a startup partly owned by the Chinese Academy of Agricultural Sciences, started to commercialize its own Bt cotton seed, which it was able to sell for half the price. The company quickly overtook Monsanto, and today its seed commands almost the entire Chinese cotton market. It is not hard to imagine that China could repeat the feat with corn, soybeans, and other crops (Qifa Zhang is working with another major Chinese seed company, China National Seed, on rice). China has restricted R&D by multinational seed companies, leaving the market wide open to local firms. And since most of the results would be consumed within China, those companies wouldn't have to worry about regulations in the GMO-skittish European Union or elsewhere.

Yet even promising startups—ones encouraged by the government—are holding back on GMOs. A few years ago, Xing Wang Deng arrived in Beijing to start a lab at Peking University through China's 1,000 Talents Program, which attempts to bring Chinese-born experts back from abroad. A native of rural Hunan province, he had earned a PhD at the University of California, Berkeley, and wound up running his own lab at Yale. There, he led basic research into understanding how plants respond to light stimuli.

Since Deng has extensive experience identifying the functions of plant genes, he's in the perfect position to guide research using next-generation, highly precise genetic tools to subtly change crop genomes. During my visit, a brand-new lab space was being readied on campus; a few miles away stood new office space for his startup company, Frontier Laboratories.

But Deng won't include GMOs in his initial batch of products. He's trying to develop hybrid rice and wheat varieties using chemically induced mutations and molecular biology techniques such as looking at genetic markers to aid conventional breeding. He's even working on ways to make crops herbicide-resistant without adding genes from soil bacteria. "These might yield similar results to genetic modification," he says. Deng's delicate dance to avoid the GMO label is a sign of the social and political climate—for now. "It seems the government is not in a rush," he says. "It probably has more challenging issues on its hands, so this is not one to deal with at the moment. The [need for] GMOs is not rising to [such a] crisis that the government has to deal with it."

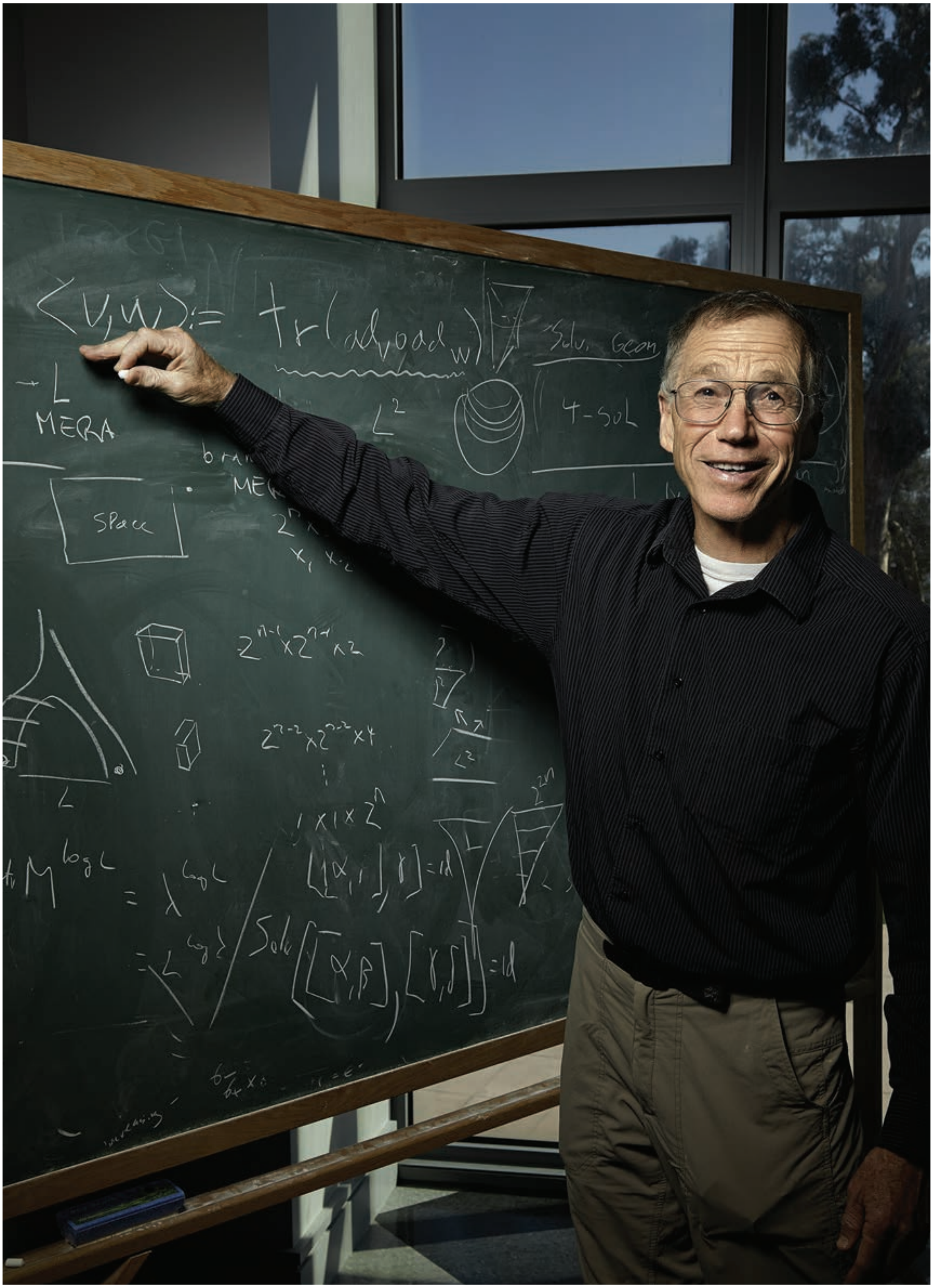
Nobody knows when China will begin deploying its GMO stockpile. But few doubt that at some point the government will decide to plant what it has been developing in its labs.

Crises will come. The Chinese government that wants to avoiding provoking the outrage of its GMO-wary citizens may at some point face a broader and even more distressed constituency: farmers watching crops dying, and citizens who can't afford—or even find—enough food. Temperature increases and precipitation decreases could slash China's net yields of rice, wheat, and corn by 13 percent over the next 35 years, according to an analysis by scientists at Peking University's Center for Climate Research. Even an outcome that merely keeps yields flat would be catastrophic in the face of population growth and rising demand. "If we have some very serious agricultural disasters for the government officials, they have to make decisions to push the commercialization of GMOs," says Dafang Huang.

Even if China can increase yields by improving existing agricultural practices, as it probably can, Rozelle and other China watchers expect the country to approve GM corn at some point; the demand for corn for animal feed will become too urgent, and using the crop for animal feed is far less controversial than growing it for human consumption. Nobody knows when or to what extent China will begin deploying its GMO stockpile to feed its citizens.

But few doubt that at some point, when costs rise and supply gets tighter, the government will decide it's time to plant what it has been developing in its labs. And when that happens, given China's centrally managed economy, farms and families can be expected to adopt the technology quickly. "Once the official attitude is changed, everything will be changed very soon," says Huang. And in the decades to come, if one of the innumerable GMO strains sprouting in the labs of Gao and others should help get the nation through a mega-drought or pronounced heat wave, that fix might well seem museum-worthy to future curators of Chinese agricultural history.

David Talbot is chief correspondent of MIT Technology Review.



Michael Freedman directs Station Q.

Portrait by Joseph Escamilla

MIT TECHNOLOGY REVIEW
VOL. 117 | NO. 6

Microsoft's Quantum Mechanics

Can an aging corporation's adventures in fundamental physics open an era of unimaginably powerful computers?

by Tom Simonite

IN 2012, PHYSICISTS IN THE NETHERLANDS announced a discovery in particle physics that started chatter about a Nobel Prize. Inside a tiny rod of semiconductor crystal chilled cooler than outer space, they had caught the first glimpse of a strange particle called the Majorana fermion, finally confirming a prediction made in 1937. It was an advance seemingly unrelated to the challenges of selling office productivity software or competing with Amazon in cloud computing, but Craig Mundie, then heading Microsoft's technology and research strategy, was delighted. The abstruse discovery—partly underwritten by Microsoft—was crucial to a project at the company aimed at making it possible to build immensely powerful computers that crunch data using quantum physics. "It was a pivotal moment," says Mundie. "This research was guiding us toward a way of realizing one of these systems."

Microsoft is now almost a decade into that project and has just begun to talk publicly about it. If it succeeds, the world could change dramatically. Since the physicist Richard Feynman first suggested the idea of a quantum computer in 1982, theorists have proved that such a machine could solve problems that would take the fastest conventional computers hundreds of millions of years or longer. Quantum computers might, for example, give researchers better tools to design novel medicines or super-efficient solar cells. They could revolutionize artificial intelligence.

Progress toward that computational nirvana has been slow because no one has been able to make a reliable enough version of the basic building block of a quantum computer: a quantum bit, or qubit, which uses quantum effects to encode data. Academic and government researchers and corporate labs at IBM and Hewlett-Packard have all built them. Small numbers have been wired together, and the resulting devices are improving. But no one can control the physics well enough for these qubits to serve as the basis of a practical general-purpose computer.

Microsoft has yet to even build a qubit. But in the kind of paradox that can be expected in the realm of quantum physics, it may also be closer than anyone else to making quantum computers practical. The company is developing a new kind of qubit, known as a topological qubit, based largely on that 2012 discovery in the Netherlands. There's good reason to believe this design will be immune from the flakiness plaguing existing qubits. It will be better suited to mass production, too. "What we're doing is analogous to setting out to make the first transistor," says Peter Lee, Microsoft's head of research. His company is also working on how the circuits of a computer made with topological qubits might be designed and controlled. And Microsoft researchers working on algorithms for quantum computers have shown that a machine made

up of only hundreds of qubits could run chemistry simulations beyond the capacity of any existing supercomputer.

In the next year or so, physics labs supported by Microsoft will begin testing crucial pieces of its qubit design, following a blueprint developed by an outdoorsy math genius. If those tests work out, a corporation widely thought to be stuck in computing's past may unlock its future.

Stranger still: a physicist at the fabled but faded Bell Labs might get there first.

Tied Up in Knots

In a sunny room 100 yards from the Pacific Ocean, Michael Freedman, the instigator and technical mastermind of Microsoft's project, admits to feeling inferior. "When you start thinking about quantum computing, you realize that you yourself are some kind of clunky chemical analog computer," he says. Freedman, who is 63, is director of Station Q, the Microsoft research group that leads the effort to create a topological qubit, working from a dozen or so offices on the campus of the University of California, Santa Barbara. Fit and tanned, he has dust on his shoes from walking down a beach path to lunch.

If his mind is a clunky chemical computer, it is an extraordinary one. A mathematical prodigy who entered UC Berkeley at the age of 16 and grad school two years later, Freedman was 30 when he solved a version of one of the longest-standing problems in mathematics, the Poincaré conjecture. He worked it out without writing anything down, visualizing the distortion of four-dimensional shapes in his head. "I had seen my way through the argument," Freedman recalls. When he translated that inner vision into a 95-page proof, it earned the Fields Medal, the highest honor in mathematics.

That cemented Freedman's standing as a leading light in topology, the discipline concerned with properties of shapes that don't change when those shapes are distorted. (An old joke has it that topologists can't distinguish a coffee cup from a doughnut—both are surfaces punctured by a single hole.) But he was drawn into physics in 1988 after a colleague discovered a connection between some of the math describing the topology of knots and a theory explaining certain quantum phenomena. "It was a beautiful thing," says Freedman. He immediately saw that this connection could allow a machine governed by that same quantum physics to solve problems too hard for conventional computers. Ignorant that the concept of quantum computing already existed, he had independently reinvented it.

Freedman kept working on that idea, and in 1997 he joined Microsoft's research group on theoretical math. Soon after, he teamed up with a Russian theoretical physicist, Alexei Kitaev, who had proved that a "topological qubit" formed by the same physics could be much more reliable than qubits that other groups were building. Freedman eventually began to feel he was onto something that deserved attention beyond his rarefied world of deep math and physics. In 2004, he showed up at Craig Mundie's office and announced that he saw a way to build a qubit dependable enough to scale up. "I ended up sort of making a pitch," says Freedman. "It looked like if you wanted to start to build the technology, you could."

Mundie bought it. Though Microsoft hadn't been trying to develop quantum

Quantum Projects

COMPANY	TECHNOLOGY	WHY IT COULD FAIL
IBM	Makes qubits from superconducting metal circuits.	The error rate of the qubits is too high to operate them together in a useful computer.
Microsoft	Building a new kind of "topological qubit" that in theory should be more reliable than others.	The existence of the subatomic particle used in this qubit remains unproven. Even if it is real, there isn't yet evidence it can be controlled.
Alcatel-Lucent	Inspired by Microsoft's research, it is pursuing a topological qubit based on a different material.	Same as above.
D-Wave Systems	Sells computers based on superconducting chips with 512 qubits.	It's not clear that its chips harness quantum effects. Even if they do, their design is limited to solving a narrow set of mathematical problems.
Google	After experimenting with D-Wave's computers since 2009, it recently opened a lab to build chips like D-Wave's.	Same as above. Plus, Google is trying to adapt technology first developed for a different kind of qubit to the kind used by D-Wave.

computers, he knew about their remarkable potential and the slow progress that had been made toward building them. "I was immediately fascinated by the idea that maybe there was a completely different approach," he says. "Such a form of computing would probably turn out to be the basis of a transformation akin to what classical computing has done for the planet in the last 60 years." He set up an effort to create the topological qubit, with a slightly nervous Freedman at the helm. "Never in my life had I even built a transistor radio," Freedman says.

Distant Dream

In some ways, a quantum computer wouldn't be so different from a conventional one. Both deal in bits of data represented in binary form. And both types of machine are made up of basic units that represent bits by flipping between different states like a switch. In a conventional computer, every tiny transistor on a chip can be flipped either off to signify a *0* or on for a *1*. But because of the quirky rules of quantum physics, which govern the behavior of matter and energy at extremely tiny scales, qubits can perform tricks that make them exceedingly powerful. A qubit can enter a quantum state known as superposition, which effectively represents *0* and *1* at the same time. Once in a superposition state, qubits can become linked, or "entangled," in a way that means any operation affecting one instantly changes the fate of another. Because of superposition and entanglement, a single operation in a quantum computer can execute parts of a calculation that would take many, many more operations for an equivalent number of ordinary bits. A quantum computer can essentially explore a huge number of possible computational pathways in parallel. For some types of problems, a quantum computer's advantage over a conventional one grows exponentially with the amount of data to be crunched. "Their power is still an amazement to me," says Raymond Laflamme, executive director of the Institute for Quantum Computing at the University of Waterloo, in Ontario. "They change the foundation of computer science and what we mean by what is computable."

But pure quantum states are very fragile and can be observed and controlled only in carefully contrived circumstances. For a superposition to be stable, the qubit must be shielded from seemingly trivial noise such as random bumping from subatomic particles or faint electrical fields from nearby electronics. The two best current qubit technologies represent bits in the magnetic properties of individual charged atoms trapped in magnetic fields or as the tiny current inside circuits of superconducting metal. They can preserve superpositions for no longer than fractions of a second before they collapse in a process known as decoherence. The largest number of qubits that have been operated together is just seven.

In the next year or so, physics labs supported by Microsoft will begin testing its qubit design.

Since 2009, Google has been testing a machine marketed by the startup D-Wave Systems as the world's first commercial quantum computer, and in 2013 it bought a version of the machine that has 512 qubits. But those qubits are hardwired into a circuit for a particular algorithm, limiting the range of problems they can work on. If successful, this approach would create the quantum-computing equivalent of a pair of pliers—a useful tool suited to only some tasks. The conventional approach being pursued by Microsoft offers a fully programmable computer—the equivalent of a full toolbox. And besides, independent researchers have been unable to confirm that D-Wave's machine truly functions as a quantum computer. Google recently started its own hardware lab to try to create a version of the technology that delivers.

The search for ways to fight decoherence and the errors it introduces into calculations has come to dominate the field of quantum computing. For a qubit to truly be scalable, it would probably need to accidentally decohere only around once in a million operations, says Chris Monroe, a professor at the University of Maryland and co-leader of a quantum computing project funded by the Department of Defense and the Intelligence Advanced Research Projects Activity. Today the best qubits typically decohere thousands of times that often.

Microsoft's Station Q might have a better approach. The quantum states that lured Freedman into physics—which occur when electrons are trapped in a plane inside certain materials—should provide the stability that a qubit builder craves, because they are naturally deaf to much

of the noise that destabilizes conventional qubits. Inside these materials, electrons take on strange properties at temperatures close to absolute zero, forming what are known as electron liquids. The collective quantum properties of the electron liquids can be used to signify a bit. The elegance of the design, along with grants of cash, equipment, and computing time, has lured some of the world's leading physics researchers to collaborate with Microsoft. (The company won't say what fraction of its $11 billion annual R&D spending goes to the project.)

The catch is that the physics remains unproven. To use the quantum properties of electron liquids as bits, researchers would have to manipulate certain particles inside them, known as non-Abelian anyons, so that they loop around one another. And while physicists expect that non-Abelian anyons exist, none have been conclusively detected.

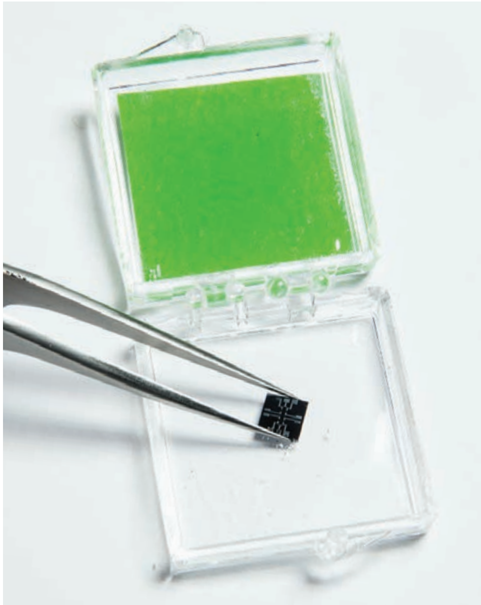
Majorana particles, the kind of non-Abelian anyons that Station Q and its collaborators seek, are particularly elusive. First predicted by the reclusive Italian physicist Ettore Majorana in 1937, not long before he mysteriously disappeared, they have captivated physicists for decades because they have the unique property of being their own antiparticles, so if two ever meet, they annihilate each other in a flash of energy.

No one had reported credible evidence that they existed until 2012, when Leo Kouwenhoven at Delft University of Technology in the Netherlands, who had gotten funding and guidance from Microsoft, announced that he had found them inside nanowires made from the semiconductor indium antimonide. He had coaxed the right kind of electron liquid into existence by connecting the nanowire to a chunk of superconducting electrode at one end and an ordinary one at the other. It offered the strongest support yet for Microsoft's design. "The finding has given us tremendous confidence that we're really onto something," says Microsoft's Lee. Kouwenhoven's group and other labs are now trying to refine the results of the experiment and show that the particles can be manipulated. To speed progress and set the stage for possible mass production, Microsoft has begun working with industrial companies to secure supplies of semiconductor nanowires and the superconducting electronics that would be needed to control a topological qubit.

For all that, Microsoft doesn't yet have its qubit. A way must be found to move

Bob Willett's quantum computing research at Bell Labs is showing promise.

STEPHANIE DIANI



One of the crystals on which Willett says he has detected topological qubits.

Majorana particles around one another in the operation needed to write the equivalent of *0*s and *1*s. Materials scientists at the Niels Bohr Institute in Copenhagen recently found a way to build nanowires with side branches, which could allow one particle to duck to the side while another passes. Charlie Marcus, a researcher there who has worked with Microsoft since its first design, is now preparing to build a working system with the new wires. "I would say that is going to keep us busy for the next year," he says.

Success would validate Microsoft's qubit design and put an end to recent suggestions that Kouwenhoven may not have detected the Majorana particle in 2012 after all. But John Preskill, a professor of theoretical physics at Caltech, says the topological qubit remains nothing more than a nice theory. "I'm very fond of the idea, but after some years of serious effort there's still no firm evidence," he says.

Competitive Physics

At Bell Labs in New Jersey, Bob Willett says he has seen the evidence. He peers over his glasses at a dull black crystal rectangle the size of a fingertip. It has hand-soldered wires around its edges and fine zigzags of aluminum on its surface. And in the middle of the chip, in an area less than a micrometer across, Willett reports detecting non-Abelian anyons. If he is right, Willett is farther along than anyone who is working with Microsoft. And in his series of small, careworn labs, he is now preparing to build what—if it works—will be the world's first topological qubit. "We're making the transition from the science to the technology now," he says. His effort has historical echoes. Down the corridor from his labs, past a giant bust of Alexander Graham Bell, is a glass display case with the first transistor inside, made on this site in 1947.

Willett's device is a version of a design that Microsoft has mostly given up on. By the time the company's project began, Freedman and his collaborators had determined that it should be possible to build a topological qubit using crystals of ultrapure gallium arsenide that trap electrons. But in four years of experiments, the physics labs supported by Microsoft didn't find conclusive evidence of non-Abelian anyons. Willett had worked on similar physics for years, and after reading a paper of Freedman's on the design, he decided to have a go himself. In a series of papers published between 2009 and 2013, he reported finding those crucial particles in his own crystal-based devices. When one crystal is cooled with liquid helium to less than 1 Kelvin (−272.15 °C) and subjected to a magnetic field, an electron liquid forms at its center. Willett uses electrodes to stream the particles around its edge; if they are non-Abelian anyons looping around their counterparts in the center, they should change the topological state of the electron liquid as a whole. He has published results from several different experiments in which he saw telltale wobbles, which theorists had predicted, in the current of those flowing particles. He's now moved on to building a qubit design. It is not much more complex than his first experiment: just two of the same circuits placed back to back on the same crystal, with extra electrodes that link electron liquids and can encode and read out quantum states that represent the equivalent of *0*s and *1*s.

Willett hopes that device will squelch skepticism about his results, which no one else has been able to replicate. Microsoft's collaborator Charlie Marcus says Willett "saw signals that we didn't see." Willett counters that Marcus and others have made their devices too large and used crystals with important differences in their properties. He says he recently confirmed that by testing some devices made to the specifications used by other researchers. "Having worked with the materials they're working with, I can see why they stopped doing it, because it is a pain in the ass," he says.

Bell Labs, now owned by the French telecommunications company Alcatel-Lucent, is smaller and poorer than it was back when AT&T, unchallenged as the American telephone monopoly, let many researchers do pretty much anything they desired. Some of Willett's rooms overlook the dusty, scarred ground left when an entire wing of the lab was demolished this year. But with fewer people around than the labs had long ago, it's easier to get access to the equipment he needs, he

says. And Alcatel has begun to invest more in his project. Willett used to work with just three other physicists, but recently he began collaborating with mathematicians and optics experts too. Bell Labs management has been asking about the kinds of problems that might be solved with a small number of qubits. "It's expanding into a relatively big effort," he says.

Willett sees himself as an academic colleague of the Microsoft researchers rather than a corporate competitor, and he still gets invited to Freedman's twice-yearly symposiums that bring Microsoft collaborators and other leading physicists to Santa Barbara. But Microsoft management has been more evident at recent meetings, Willett says, and he has sometimes felt that his being from another corporation made things awkward.

"We believe that there's a chance to do something that could be the foundation of a whole new economy."

It would be more than just awkward if Willett beat Microsoft to proving that the idea it has championed can work. For Microsoft to open up a practical route to quantum computing would be surprising. For the withered Bell Labs, owned by a company not even in the computing business, it would be astounding.

Quantum Code

On Microsoft's leafy campus in Redmond, Washington, thousands of software engineers toil to fix bugs and add features to Windows and Microsoft Office. Tourists pose in the company museum for photos with a life-size cutout of a 1978 Bill Gates and his first employees. In the main research building, Krysta Svore leads a dozen people working on software for computers that may never exist. The team is figuring out what the first generation of quantum computers could do for us.

The group was established because although quantum computers would be powerful, they cannot solve every problem. And only a handful of quantum algorithms have been developed in enough detail to suggest that they could be practical on real hardware. "Quantum computing is possibly very disruptive, but we need to understand where the power is," Svore says.

No quantum computer is ever going to fit into your pocket, because of the way qubits need to be supercooled (unless, of course, someone uses a quantum computer to design a better qubit). Rather, they would be used like data centers or supercomputers to power services over the Internet, or to solve problems that allow other technologies to be improved. One promising idea is to use quantum computers for superpowered chemistry simulations that could accelerate progress on major problems in areas such as health or energy. A quantum computer could simulate reality so precisely that it could replace years of plodding lab work, says Svore. Today roughly a third of U.S. supercomputer time is dedicated to simulations for chemistry or materials science, according to the Department of Energy. Svore's group has developed an algorithm that would let even a first-generation quantum computer tackle much more complex problems, such as virtually testing a catalyst for removing carbon dioxide from the atmosphere, in just hours or minutes. "It's a potential killer application of quantum computers," she says.

But it's possible to envision countless other killer applications. Svore's group has produced some of the first evidence that quantum computers can be used for machine learning, a technology increasingly central to Microsoft and its rivals. Recent advances in image and speech recognition have triggered a frenzy of new research in artificial intelligence. But they rely on clusters of thousands of computers working together, and the results still lag far behind human capabilities. Quantum computers might overcome the technology's limitations.

Work like that helps explain how the first company to build a quantum computer might gain an advantage virtually unprecedented in the history of technology. "We believe that there's a chance to do something that could be the foundation of a whole new economy," says Microsoft's Peter Lee. As you would expect, he and all the others working on quantum hardware say they are optimistic. But with so much still to do, the prize feels as distant as ever. It's as if qubit technology is in a superposition between changing the world and decohering into nothing more than a series of obscure research papers. That's the kind of imponderable that people working on quantum technology have to handle every day. But with a payoff so big, who can blame them for taking a whack at it? T

Tom Simonite is MIT Technology Review*'s San Francisco bureau chief.*

PUJIANG INNOVATION FORUM
浦江创新论坛

2014 协同创新 共享机遇
Coordinated Innovation and Sharing Opportunities

China's Path to Innovation

25-26 October, 2014
Shanghai, China

WWW.PUJIANGFORUM.ORG

Key Activities:

Opening Ceremony & Plenary Session	
Country of Honor Forum	Enhance the Collaborations between Russia and China in the Field of Science & Innovation
The Regional & Urban Forum	Seeking Quality: Improving the Quality of Urbanization through Innovation
The Industry Forum	Welcoming Changes: New Directions and New Situations in the Industrial Transformation and Upgrade
The Policy Forum	Policy Guide: Stimulation of Innovation Energy in Markets
The Entrepreneur Forum	Young Entrepreneurs: Let Young People be the Leader of Changes
The Future Science Forum	Exploring the Frontiers of Knowledge
The Enterprise Forum	Open Innovation: Enterprises in Global Perspective
The Culture Forum	Trust: Social Networks and Innovation Partners

Hosts: Ministry of Science and Technology of the People's Republic of China
Shanghai Municipal People's Government

Contact: Helen Li
Tel: +86-21-54065309, E-mail: pif@pujiangforum.org

The disparity between the rich and everyone else is larger than ever in the United States and increasing in much of Europe. Why?

Technology and Inequality

By David Rotman

Illustration by Javier Jaén

The signs of the gap—really, a chasm—between the poor and the super-rich are hard to miss in Silicon Valley. On a bustling morning in downtown Palo Alto, the center of today's technology boom, apparently homeless people and their meager belongings occupy almost every available public bench. Twenty minutes away in San Jose, the largest city in the Valley, a camp of homeless people known as the Jungle—reputed to be the largest in the country—has taken root along a creek within walking distance of Adobe's headquarters and the gleaming, ultramodern city hall.

The homeless are the most visible signs of poverty in the region. But the numbers back up first impressions. Median income in Silicon Valley reached $94,000 in 2013, far above the national median of around $53,000. Yet an estimated 31 percent of jobs pay $16 per hour or less, below what is needed to support a family in an area with notoriously expensive housing. The poverty rate in Santa Clara County, the heart of Silicon Valley, is around 19 percent, according to calculations that factor in the high cost of living.

Even some of the area's biggest technology boosters are appalled. "You have people begging in the street on University Avenue [Palo Alto's main street]," says Vivek Wadhwa, a fellow at Stanford University's Rock Center for Corporate Governance and at Singularity University, an education corporation in Moffett Field with ties to the elites in Silicon Valley. "It's like what you see in India," adds Wadhwa, who was born in Delhi. "Silicon Valley is a look at the future we're creating, and it's really disturbing." Many of those made rich by the recent technology boom, he adds, don't seem to care about "the mess they're creating."

The wealth generated in Silicon Valley is "as prodigious as it has ever been," says Russell Hancock, president of Joint Venture Silicon Valley, a nonprofit group that promotes regional development. "But when we used to have booms in the tech sector, it would lift all boats. That's not how it works anymore. And suddenly you're seeing a backlash and people are upset." Indeed, people are stoning buses transporting Google employees to work from their homes in San Francisco.

The anger in Northern California and elsewhere in the United States springs from an increasingly obvious reality: the rich are getting richer while many other people are struggling. It's hard not to wonder whether Silicon Valley, rather than just exemplifying this growing inequality, is actually contributing to it, by producing digital technologies that eliminate the need for many middle-class jobs. Here, technology is arguably evolving faster than anywhere else in the world. Does the region really portend a future, as Wadhwa would have it, in which a few very rich people leave the rest of us hopelessly behind?

The desire to understand why inequality seems to be reaching such troubling levels no doubt accounts for the remarkable success this year of the French academic economist Thomas Piketty's *Capital in the Twenty-First Century*, which its publisher sold out soon after its initial publication. With its multitude of equations, its references to the Belle Époque and Ancien Régime, and a title that harks back to Karl Marx and the politics of the late 19th and early 20th centuries, the 700-page tome seemed an unlikely candidate for popular reading. Yet it quickly rose to the top of best-seller lists this spring and remained on them for months.

Economists have long warned that inflation-adjusted wages for low- and middle-income workers have been flat or declining since the late 1970s in the United States, even as its economy has grown. Piketty, a professor at the Paris School of Economics, greatly expands on this idea, documenting the exploding wealth of the very rich in the United States and Europe and comparing the trend with developments over the last few centuries. Building on research conducted with his colleagues Emmanuel Saez, a professor at the University of California, Berkeley, and Anthony Atkinson, an economist at the University of Oxford, Piketty collected and analyzed data, including tax records, to show just how extreme the disparity in wealth between the rich and the rest of the population has grown. (The story necessarily revolves around the United States, France, and several other European countries in which such historical data are available.)

The gap between the wealthy and everyone else is largest in the United States. The richest 1 percent of the population has 34 percent of the accumulated wealth; the top 0.1 percent has some 15 percent.

The gap between the wealthy and everyone else is largest in the United States. In 2010, the richest 1 percent of the population had 34 percent of the accumulated wealth; the top 0.1 percent had some 15 percent. And the inequality has only gotten worse since the last recession ended: the top 1 percent captured 95 percent of income growth from 2009 to 2012, if capital gains are included.

The top 10 percent now accounts for 48 percent of national income; the top 1 percent makes almost 20 percent and the top 0.1 makes nearly 9 percent. The disparity in the portion of income earned from work—what economists call labor income—is particularly striking. Wage inequality in the United States is "probably higher than in any other society at any time in the past, anywhere in the world," writes Piketty.

Why is this going on? Piketty attributes it in part to unjustifiably large salaries for people he calls "supermanagers." About 70 percent of the top 0.1 percent of earners are corporate executives, by his calculations. "The standard explanation for rising inequality is the race between the demand and the supply for high skills," he told me. "I think that this is an important part of the overall explanation. But this is not all. In order to explain why rising inequality has been so strong at the very top in the U.S., one needs more than a skill-based explanation." Piketty points to "pay-setting institutions and corporate governance" as factors. He adds, "Above a certain level, it is very hard to find in the data any link between pay and performance."

In Britain and France the overall rise of inequality is less dramatic, but in those countries something else is happening that could be even more worrisome: accumulated wealth, much of it inherited, is returning to relative levels not seen since before the First World War. Privately held wealth in some European countries is now about 500 to 600 percent of annual national income, a level approaching that of the early 1900s.

What particularly worries Piketty is the long-term effect of this concentration of wealth. A central point of his book is the simple statement $r > g$, where r is the average return on capital and g is the economic growth rate. When the rate of return on capital exceeds the growth rate (which he says is what happened until the beginning of the 20th century and is likely to happen again as growth slows), then the money that rich people make from their wealth piles up while wages rise more slowly if at all.

The implications of this should be frightening for anyone who believes in a merit-based system. It means we are in danger of entering into an era that, like the 19th century in France and England, is socially and politically dominated by those with vast amounts of inherited wealth. Piketty describes it as the world of Jane Austen, in which people's lives and fates are determined by their inheritance and not their talents or professional achievements.

As Piketty points out, it is a radical departure from how we have thought about progress. Since the 1950s, economics has been dominated by the idea—notably formulated by Simon Kuznets, a Harvard economist and Nobel laureate—that inequality diminishes as countries become more technologically developed and more people are able to take advantage of the resulting opportunities. Many of us suppose that our talents, skills, training, and acumen will allow us to prosper; it is what economists like to call "human capital." But the belief that technological progress will lead to "the triumph of human capital over financial capital and real estate, capable managers over fat cat stockholders, and skill over nepotism" is, writes Piketty, "largely illusory."

Not all economists are so pessimistic; in fact, g has been higher than r for most of the 20th century and continues to be so. Nonetheless, Piketty's book is important because of the way he has clarified the magnitude of the problem and its dangers. And he has done so at a time of increasing soul-searching about the role technology plays in exacerbating inequality. "It just seems so obvious to me [that] technology is accelerating the rich-poor gap," says Steve Jurvetson, a venture capitalist at DFJ Venture in Menlo Park, California. In many discussions with his peers in the high-tech community, he says, it has been "the elephant in the room, stomping around, banging off the walls."

Still, as Piketty's lengthy analysis suggests, the explanation for the rise in inequality is not a simple one. Specifically, the role technology is playing is complex—and contested.

Racing Ahead

"My reading of the data is that technology is the main driver of the recent increases in inequality. It's the biggest factor," says Erik Brynjolfsson, a professor of management at MIT's Sloan School. The coauthor, with fellow MIT academic Andrew McAfee, of *The Second Machine Age*, Brynjolfsson, like Piketty, has recently gained unlikely prominence for an academic economist.

Piketty and Brynjolfsson both earned their degrees in the early 1990s, and both were professors at MIT during the following years. But beyond an agreement that growing inequality is a problem, their thinking could hardly be more different. While Piketty's writing is sprinkled with references to Jane Austen and Honoré de Balzac, Brynjolfsson talks of advanced robots and the vast potential of artificial intelligence. While Piketty warns against a return to a world where inherited wealth determines social and political fates, Brynjolfsson worries that a growing share of the workforce could be left behind even as digital technologies increase overall income.

Central to Brynjolfsson's argument is the idea that innovation is rapidly accelerating as trends in computing and net-

The biggest factor is that the technology-driven economy greatly favors a small group of successful individuals by amplifying their talent and luck.

working advance at an exponential rate. Largely as a result of these advances, productivity and GDP continue to increase. But while "the pie is increasing," he says, not everyone is benefiting. (Brynjolfsson notes that productivity has, according to conventional measurements, grown slowly since around 2005. But he attributes that "disappointing" slowdown to the recession and its aftermath—and, perhaps most important, to the fact that organizations have yet to fully capture the benefits expected to come from digital technologies.)

Brynjolfsson lists several ways that technological changes can contribute to inequality: robots and automation, for example, are eliminating some routine jobs while requiring new skills in others (see "How Technology Is Destroying Jobs," July/August 2013). But the biggest factor, he says, is that the technology-driven economy greatly favors a small group of successful individuals by amplifying their talent and luck, and dramatically increasing their rewards.

Brynjolfsson argues that these people are benefiting from a winner-take-all effect originally described by Sherwin Rosen in a 1981 paper called "The Economics of Superstars." Rosen said that such breakthroughs as motion pictures, radio, and TV had greatly broadened the audiences—and hence the rewards—for those in show business and sports. Thirty years later, Brynjolfsson sees a similar effect for high-tech entrepreneurs, whose ideas and products can be widely distributed and produced thanks to software and other digital technologies. Why hire a local tax consultant when you can use a cheap, state-of-the-art program that is constantly being updated and refined? Likewise, why buy a second-best program or app? The ability to copy software and distribute digital products anywhere means customers will buy the top one. Why use a search engine that is *almost* as good as Google? Such economic logic now rules a growing share of the marketplace; it is, according to Brynjolfsson, an increasingly important reason why a few entrepreneurs, including the founders of such startups as Instagram, are growing rich at a staggering rate.

The distinction between Piketty's supermanagers and Brynjolfsson's superstars is critical: the latter derive their high incomes directly from the effects of technology. As machines increasingly substitute for labor and building a business becomes less capital-intensive—you don't need a printing plant to produce an online news site, or large investments to create an app—the biggest economic winners will not be those owning conventional capital but, instead, those with the ideas behind innovative new products and successful business models.

In an article called "New World Order," published this summer in *Foreign Affairs*, Brynjolfsson, McAfee, and Michael Spence, a Nobel laureate and professor at New York University, argued that "superstar-based technical change … is upending the global economy." That economy, they conclude, will increasingly be dominated by members of the small elite that "innovate and create."

Stay in School

The exploding wealth of the very rich is only one part of the story of inequality. For much of the population, incomes have stagnated or even shrunk, and technology is one of the leading culprits. Simply put, as we getter better at automating routine tasks, the people who benefit most are those with the expertise and creativity to use these advances. And that drives income inequality: demand for highly skilled workers rises, while workers with less education and expertise fall behind.

Though income growth among the top 1 percent is an important phenomenon, says David Autor, an MIT economist, the disparity in skills and education among the other 99 percent is "a big deal, a much bigger deal." The gap between median earnings for people with a high school diploma and those with a college degree was $17,411 for men and $12,887 for women in 1979; by 2012 it had risen to $34,969 and $23,280. Education, Autor says, "is the most powerful thing you can do to affect lifetime earnings."

In the United States, this education premium began rising steeply in the late 1970s, when the surge of college entrants dramatically slowed and the availability of high-skill workers consequently dwindled. More recent decades have seen an additional twist. Automation and digital technologies have reduced

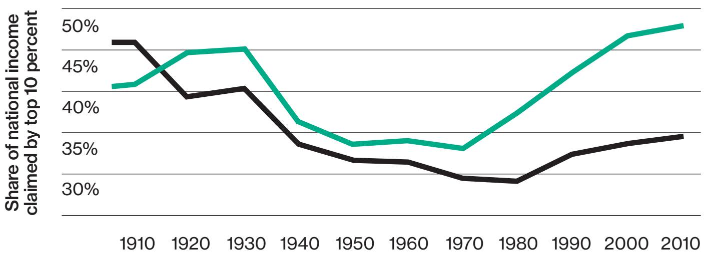
SOURCES: THOMAS PIKETTY, CENTER ON BUDGET AND POLICY PRIORITIES, DAVID AUTOR, THE WORLD TOP INCOME DATABASE

The Inequality Problem

Inequality is growing particularly fast in the United States, while accumulated wealth as a percentage of national income is rising in Europe. In the aftermath of the recession, much of the recovery went to the very rich. Meanwhile, those with low levels of education are falling further behind.

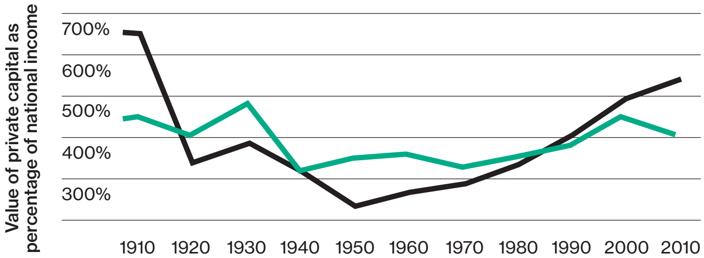
Income inequality in Europe and the United States

U.S.
Europe

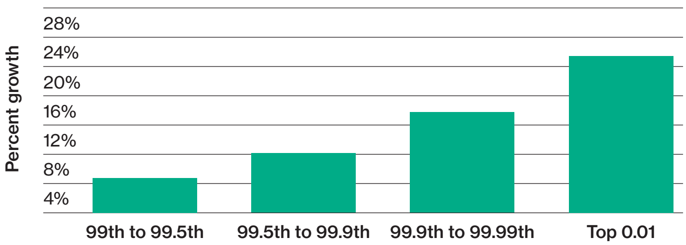


Wealth-to-income ratio in Europe and the United States

U.S.
Europe

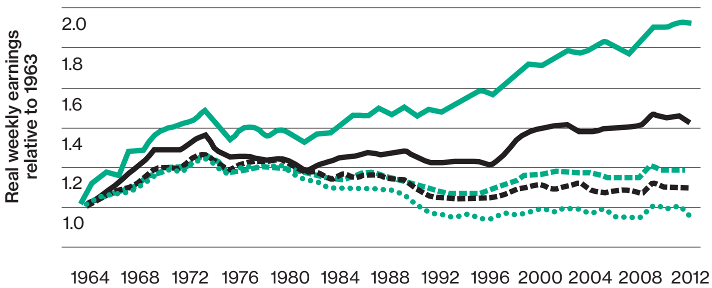


Growth in income for households within the top percentile, 2009–2010



Change in real wage levels in U.S. by education (men)

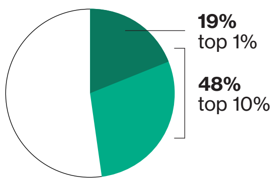
> Bachelor's degree
Bachelor's degree
Some college
High school graduate
High school dropout



Average U.S. income
(in 2012 dollars)

1970	Top 10%	$137,223
	Bottom 90%	$33,135
1975	10%	$138,384
	90%	$31,759
1980	10%	$142,808
	90%	$32,413
1985	10%	$150,599
	90%	$32,120
1990	10%	$184,843
	90%	$32,345
1995	10%	$194,933
	90%	$31,768
2000	10%	$244,153
	90%	$35,799
2005	10%	$247,452
	90%	$33,688
2010	10%	$239,813
	90%	$30,840
2012	10%	$254,449
	90%	$30,439

U.S. income share (2012)



the need for many production, sales, administrative, and clerical jobs, while demand has increased for low-pay jobs that can't be automated, such as those in cleaning services and restaurants. The result has been what Autor describes as a "barbell-shaped" job market, with strong demand at the high and low ends and a "hollowing out" of the middle. And despite the increase in demand for workers in service jobs, there is an ample supply of people who need the work and can do these tasks. Hence wages for these jobs dropped throughout much of the 2000s, further worsening income inequality.

Autor, for one, is skeptical of Brynjolfsson and McAfee's argument that the transformation of work is speeding up as technological change accelerates. Research he conducted with a fellow MIT economist, Daron Acemoglu, suggests that productivity growth is not in fact accelerating, nor is such growth concentrated in computer-intensive sectors. According to Autor, the changes wrought by digital technologies *are* transforming the economy, but the pace of that change is not necessarily increasing. He says that's because progress in robotics, artificial intelligence, and such high-profile technologies as Google's driverless car are happening more slowly than some people may think. Despite impressive anecdotal accounts, these technologies are not ready for widespread use. "You would be actually pretty hard pressed to find a robot in your day-to-day life," he observes.

Indeed, Autor believes many tasks that people are particularly good at, such as recognizing objects and dealing with suddenly changing environments, will remain difficult or expensive to automate for decades to come. The implications for inequality are significant: it could mean that the market for middle-skill jobs may be stabilizing and the earning disparity between low- and high-skill jobs leveling off, albeit "at a very high level." What's more, many middle-skill workers could flourish as they increasingly learn to use digital technologies in their jobs.

It's an unusual spot of optimism in the inequality discussion. But the underlying problem for much of the population remains. "We have a very skill-driven economy without a very skilled workforce," Autor says. "If you have the high skills—and that's a big if—you can make a fortune."

Silicon Valley

In his quiet suite in a large office building in downtown San Jose, Joint Venture president Russell Hancock seems impatient when asked about inequality in the region. "I have more questions than answers. I can't explain it. I can't tell you how to fix it," he begins abruptly. "We used to be a classic middle-class economy. But that's all gone. There's no longer a middle class. The economy is bifurcated and there's nothing in the middle."

He blames globalization for wiping out the semiconductor industry and other high-tech manufacturing that once prospered in the region, as well as changes in technology that have eliminated well-paid jobs in administration and other support services. "There used to be a ladder to get into the middle class, and some sense of mobility," Hancock says. But that ladder, he says, is gone: "It didn't happen suddenly, but in 2014 everyone has woken up to it."

Though California's economy—the world's eighth-largest—is strong in many sectors, the state has the highest poverty rate in the country, if cost of living is factored in. The situation in Silicon Valley helps explain why. About 20 to 25 percent of the population works in the high-tech sector, and the wealth is concentrated among them. This relatively small but prosperous group is driving up the cost of housing, transportation, and other living expenses. At the same time, much of the employment growth in the area is happening in retail, restaurant, and manual jobs, where wages are stagnant or even declining. It's a simple formula for income inequality and poverty. But the nature of technology itself seems to have made it worse. According to Chris Benner, a regional economist at the University of California, Davis, there has been no net increase in jobs in Silicon Valley since 1998; digital technologies inevitably mean you can generate billions of dollars from a low employment base.

If economists are right that income inequality is fueled by disparities in skills and education, then the last chance for many people to find a route into the middle class may be in places like

"There used to be a ladder to get into the middle class, and some sense of mobility," Hancock says. But that ladder, he says, is gone: "It didn't happen suddenly, but in 2014 everyone has woken up to it."

Foothill College. Sprawling across some of Silicon Valley's most prized real estate in Los Altos Hills, the community college draws students from all over the region. Many come from its poorest areas, such as East Palo Alto and East San Jose. Ladder or no ladder, the college provides a fleeting opportunity for those students to at least get within striking distance of the elusive jobs in the "knowledge economy" that dominates the area.

Judy Miner, president of Foothill, is justifiably proud of its accomplishments. Students routinely transfer to prestigious four-year colleges, including the University of California's Berkeley and Santa Cruz campuses; as of a few years ago, 17 had gone on to MIT. But talented though some students are, Miner is also blunt about the challenges facing a school that proudly accepts "the top 100 percent of all applicants." Foothill, like other community colleges, is playing catch-up with many students who aren't academically prepared for universities. And, she says, one goal is to change their "worldview of where they fit in."

When she was growing up in San Francisco, Miner says, her achievements and aptitude opened the possibility of Harvard or Yale, but no one else in her family had gone to college, and she couldn't imagine leaving home to do so. So she commuted on the bus to Lone Mountain College, a small Catholic school that has since closed. Now, at Foothill, she works with families and local communities to expand the ambitions of students from backgrounds like hers. "Piketty says the best predictor of access to universities is parents' income," says Miner. "In California, it's the zip code."

A ribbon-cutting ceremony at East Palo Alto Academy is a poignant indication of how much needs to be done to close the zip-code divide. It's a cloudless, hot day in late August, a reminder that the region was once prized land for orchards. A handful of new two-story concrete buildings surround a courtyard holding a smattering of enthusiastic administrators and a few teachers. It's a relatively modest facility but, by all descriptions, a huge improvement over the cramped building the 13-year-old charter school occupied before.

In a city whose only public high school was shut down in the 1970s (students were bused to neighboring district schools), East Palo Alto Academy represents a noteworthy attempt to address the educational needs of the local community. The school seems to be turning around the lives of many of its 300 students. But no one needs to be reminded that less than three miles down University Avenue is the campus of Palo Alto High, a public school with multiple tennis courts, a synthetic running track, and a multimillion-dollar media center complete with rows of new iMacs and state-of-the-art video equipment. Meanwhile, East Palo Alto Academy has only just gotten a properly equipped chemistry lab, with a fume hood and storage facilities for the chemicals. The athletic facilities are a newly paved outdoor basketball court whose rims, as one student excitedly points out, actually have nets.

"One of the largest and most prominent debates in social sciences is the role of technology in inequality," says David Grusky, director of Stanford's Center on Poverty and Inequality. But "one fact that everyone agrees on," he says, is that the income gaps between those with different levels of education "account for a good share of the inequality." And, he says, "we know what the solution is. It's equalizing access to high-quality education. The problem is that we just pay lip service to it." The issue is not, as many suggest, the overall quality of education, he argues: "We have fine schools. For example, Palo Alto High School is a fine school. But everyone needs access to these types of schools. Everyone should have access to the kind of schools we routinely provide middle-class kids." (Local governments, using property taxes, supply an average of 44 percent of the funding for elementary and secondary schools in the United States, helping to fuel the disparity in educational investments between poor and rich communities.)

Perhaps technology is changing so quickly that people are slow to grasp which skills they might need, or don't understand that the demand for skilled labor will only grow. "But I don't think labor is that stupid," says Grusky. "If you're born into a poor neighborhood, you don't have access to a high-quality preschool, a high-quality primary school, and a high-quality secondary school. And then you're simply not in position to go to college." If workers aren't equipped to do the jobs that technology is creating, he says, "it's because our institutions are failing us."

Dirty Words

Understanding what causes income inequality is important because different answers suggest very different policy solutions. If, as Piketty fears, the gap between the very rich and everyone else is partly due to unjustifiably high compensation for top executives and will only worsen with the seemingly inexorable shift of wealth to the already wealthy, then it makes sense to find ways to redistribute those gains through progressive tax policies. Piketty and his colleague Emmanuel Saez believe that the tax cuts made by Margaret Thatcher and Ronald Reagan in the late 1970s and early 1980s jump-started the growth of income inequality seen today in Britain and the United States. Indeed, Piketty spends much of the last quarter of *Capital* outlining how increasingly progressive taxes, including a global wealth tax, could begin to close the economic gap.

But at least in the United States, "redistribution" is a dirty word in almost any political setting. "If we know one thing," says

"Any decent person should find ... extreme poverty coexisting in the same society with extreme wealth immoral."

Robert Solow, a professor emeritus of economics at MIT, "it's that redistributing income is not something we're very good at." And, he adds, "it's not about to happen."

Solow, a Nobel laureate who is one of the most influential economists of the last half-century, published a landmark paper in 1956 that transformed the way the profession views the critical role of technological progress in productivity and the growth of national wealth. Now 90, Solow published a lengthy and largely admiring review of *Capital* in *The New Republic* titled "Thomas Piketty Is Right," acclaiming his "new and powerful" insight that if $r > g$ holds, "the income and wealth of the rich will grow faster than the typical income from work." However, Solow told me that the struggles of Americans with middle and lower incomes represent a very different phenomenon from the growth of the super-rich—and a far more worrisome one. "Any decent person should find having extreme poverty coexisting in the same society with extreme wealth immoral," he says.

The most obvious policy recommendations point to education, including, as social scientists are increasingly learning, pre-kindergarten and other early education programs. As Sean Reardon, a sociologist at Stanford, points out, differences in educational achievement are now associated more closely with family income than they are with factors that have been more important in the past, including race and ethnic background. And researchers have shown that those differences in achievement levels are already set by the time children enter kindergarten.

Inequality in education is not only hurting the chances of poor children to get ahead, says David Grusky. It is also affecting the supply of high-skill labor. By stifling opportunities for countless talented individuals, it artificially restricts the potential pool of those with technological expertise. As a result, Grusky says, "we overpay for high-skill workers," which is damaging to the economy. In other words, the lack of access to high-quality education is not just bad for the students in East Palo Alto; it is bad for the companies a few miles away in the world's most concentrated center of technology innovation.

Of course, a diagnosis is far from a cure, and a call to improve educational opportunities is far too facile—who could argue with that? The challenges inherent in this kind of change must be acknowledged, and previous efforts to accomplish it have failed. Providing everyone with access to quality education would require us to transform our schooling system and the way we pay for it. But if differences in educational achievement based on family incomes are really what's driving inequality, Grusky worries, we can't solve the problem by letting people who have privileged access to a good education reap the advantages and then taxing their resulting higher earnings. That, he says, is "an after-the-fact Band-Aid that doesn't address the source of the problem." It will also strike many as unfairly taking money from those who have earned it. If the goal is the "merit-based inequality" that results when everyone has a fair chance to compete, Grusky argues, then we must attempt to reform educational institutions.

That's why asking whether technology causes inequality is the wrong question. Instead, we should be asking how advancing technologies have changed the relative demand for high-skill and low-skill workers, and how well we are adapting to such changes. Surely, rapid advances in technology have exacerbated discrepancies in education and skills, and the rise of digital technologies could possibly be playing a part in creating an extreme elite of the very rich. But it makes no sense to blame technology, just as it makes no sense to blame the rich. It is our institutions, including but not only our schools, that need to change. The reforms that experts recommend are numerous and varied, ranging from a higher minimum wage to stronger job protections to modifications of our tax policy. And if Piketty is right about the supermanagers, we need improved corporate governance and oversight to more closely tie compensation to executive productivity.

But a good place to start is by asking what the problem is and why we care. It is here that Piketty's book is so valuable. In particular, it reminds us how an elite class of the super-rich can both warp our political process and erode our sense of fairness.

In the technology industry where some of those elites are created, many will surely be left wondering whether the future looks more like Silicon Valley—a high-tech dynamo driving economic prosperity and wealth inequality at once—or, as Piketty would have it, more like France, increasingly dominated by inherited wealth. Is the creativity and productivity of places like Silicon Valley threatened by a future that favors the fortunes of the very rich over the ambitions of the many?

David Rotman is editor of MIT Technology Review.

CONTENTS

Find additional material for this report at technologyreview.com/business

BUSINESS REPORT

Breakthrough Factories

Manufacturing's pivotal role in nurturing innovation is being recognized from China to California. Where—and how—is it being done best?

MICHIEL VAN DEN BERG

The Big Question

Making Innovation

The hubs of advanced manufacturing will be the economic drivers of the future because innovation increasingly depends on production expertise.

● Visitors to the Crosspointe Rolls-Royce facility in Prince George County, Virginia, have to don safety glasses and steel-tipped shoes, just as they would at any traditional factory. But then things start to look different. Past the cubicles filled with programmers and support staff sits a 140,000-square-foot factory with spotless white concrete floors, bright lighting, surprisingly quiet equipment, and very few human beings.

Opened in 2011, Crosspointe is the kind of factory that makes a good backdrop to a political speech about advanced manufacturing, as President Barack Obama knew when he arrived less than a year later. It's global: the U.S. operations center of a U.K. company, it uses titanium forgings from Scotland, Germany, or the United States; shapes them into fan disks; and, after milling, polishing, and ⟶

testing, ships them off to England, Germany, or Singapore. Once there, each disk will become one of 10,000 parts in a typical engine.

It's also highly automated: $1.5 million machines made by DMG Mori Seiki do the initial milling of the disks, following steps directed by Siemens software with a minimum of human interference. On a day in early summer, eight machines were being monitored by three operators. Computer screens in front of the machine displayed instructions in pictures and text, flashing warnings when a part had not met specs or the machine needed to be serviced. Later an automated measurement machine with a probe on the end would spend eight hours inspecting 1,000-plus distinct dimensions of the part. For the next 25 years, Rolls-Royce will keep data on each part, starting with exactly how it was made. Sensors in the engine will track how the engine and its parts are holding up, and maintenance and flight data will be carefully recorded.

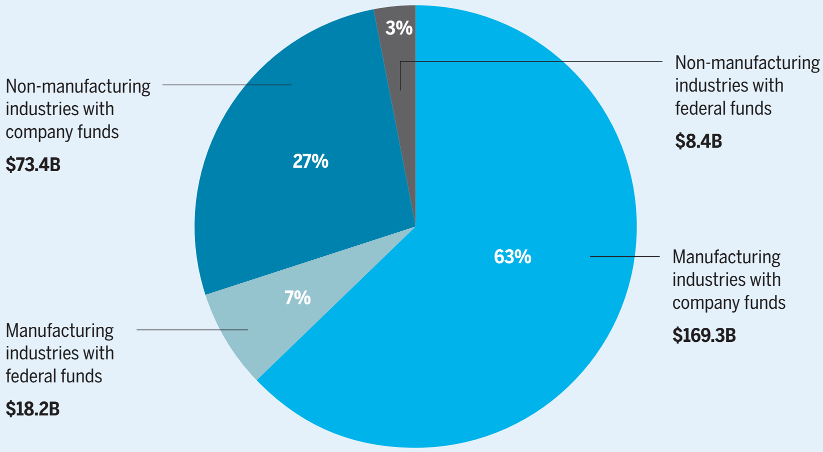
It's not just pristine floors, scarce workers, and a global network that make Crosspointe emblematic of manufacturing today. It's also the ecosystem surrounding the facility. Just down the road is the Commonwealth Center for Advanced Manufacturing, a research center whose members include Airbus, NASA, and the University of Virginia.

There, Rolls-Royce staff who know the challenges and details of manufacturing work with researchers and suppliers to improve the factory and its products, says Crosspointe manufacturing executive Lorin Sodell. "Often a great idea for a new manufacturing process won't ever make it into production because that connection is missing."

Most of the advanced machining and other innovative processes in place at Crosspointe were developed and first tested at a similar research center near the company's plant in Sheffield, U.K., called the Advanced Manufacturing Research Center. Sodell is already working with suppliers housed in the Virginia research center to diagnose and quickly address new tooling issues and any other problems that might arise.

Manufacturing and Research

Who funds U.S. industrial R&D



SOURCE: THE NATIONAL ASSOCIATION OF MANUFACTURERS

To understand why manufacturing matters, we must lose some misconceptions. First, manufacturing no longer derives its importance primarily from employing large numbers of people. As software drives more of the manufacturing process, and automated machines and robots execute much of it, factories don't need as many workers.

Second, the idea popularized in the 1990s and 2000s that innovation can happen in one place (say, Silicon Valley) while manufacturing happens in another (such as China) is not broadly sustainable. If all the manufacturing is happening in China, these networks are growing there, meaning eventually all the innovation—or at least a lot of it—will be happening there too.

10.3%
Proportion of U.S. employment that comes from manufacturing

Manufacturing will make its most essential economic contribution as an incubator of innovation: the place where new ideas become new products. Thanks to advanced manufacturing technologies, that place can in theory be pretty much anywhere. Robots, software, and sensors work no matter what language is spoken around them. In practice, however, advanced manufacturers thrive best in an ecosystem of suppliers and experienced talent. For this reason, specialized manufacturing networks have taken hold in many regions. Among the success stories highlighted in this report are China's dominance as a manufacturer of consumer electronics, Germany's lead in precision tooling and robotics, the United States' strength in aerospace and car manufacturing, and its role in pushing forward important new manufacturing technologies.

Innovative manufacturing today requires as its base that manufacturers and their suppliers build strong relationships and share knowledge extensively, says Mark Muro, a senior fellow at the Brookings Institution.

China's achievement is especially significant. Today, it would be nearly impossible for any other region to replicate the country's manufacturing prowess in electronics or the speed with which its companies can introduce new products, says Harvard Business School professor Willy Shih, a longtime executive at IBM, Eastman Kodak, and other multinational firms who studies the links between manufacturing, product development, and innovation.

It's not a new idea that manufacturing and innovation are linked. Seventy percent of industrial research and development spending in the U.S. comes from the manufacturing sector. Some have

been skeptical, however, that innovation requires manufacturing know-how.

Apple, for example, has thrived with a system of designing its products in California but having them assembled in China using digital design and manufacturing instructions. That arrangement, printed on the back of every iPhone, has been popular with investors who appreciate not only Apple's wildly successful products but also its "asset light" structure and relatively small workforce. "Couldn't everyone do what Apple did?" says MIT professor Suzanne Berger, who participated in a three-year-long university task force that examined manufacturing in hundreds of global companies and produced the book *Making in America*. "In a way, the case that motivated our whole inquiry was Apple."

Apple did not participate in the study, but in time Berger came to see that the company's case was not so black and white—that even Apple finds links between manufacturing and innovation. Apple owns the automated production machines in the Chinese factories that manufacture its products. Many California-based Apple engineers spend at least 50 percent of their time in China as new products are launched, she learned.

One engineer explained to Berger that it was critical to be on the ground in China for two reasons: to see what problems arose when the products prototyped in the U.S. hit large-scale production, and to "understand where I left too much on the table, where I could have pushed farther with the design."

After three years of study, Berger is a believer that the United States must continue to manufacture if it hopes to be an innovation leader. She finds evidence that the manufacturing communities for emerging high-tech sectors such as solar and wind energy and batteries are already being built outside the country in places where technical expertise, manufacturing skills, and even plant layouts are quickly pulling ahead.

Without manufacturing, "we lose capabilities in the workforce," says Harvard's Shih. "It limits what you are able to do down the line." —*Nanette Byrnes*

Case Study

Audi Drives Innovation on the Shop Floor

A carmaker's automated body shop illustrates how German manufacturing is moving forward.

● At first, I'm apprehensive about entering the laser chamber. Its 13-kilowatt diodes fire blasts of energy powerful enough to melt metal. At the moment, they are ready to join the roof and wall frame of an Audi A3 sedan. But the engineer at Audi's plant in Ingolstadt, Germany, insists that I see up close the "invisible" laser-brazed seam about to be made, including a minuscule bend, just five millimeters around, that prevents the car's body from corroding when exposed to the elements.

The shell of the car sits in the center of the chamber and is surrounded by robotic arms, one of which aims what looks like a soldering iron. The laser brazing process, like much else on the 540,000-square-foot factory floor, is automated and secured behind barriers or within a closed chamber. Later, when I do see people inside the factory, they tend to be pedaling down the long, spotless corridors on red bicycles.

Hubert Hartmann, head of the A3 body shop at Ingolstadt, calls it the most modern factory floor of its kind. "It is like a Swiss watch, with the same level of precision," he says as machinery whirs nearby with preprogrammed exactness. While most auto plants use robots for welding and other dangerous tasks, Audi marries a high level of automation with a multitude of other advanced manufacturing technologies, including low-power lasers driven by optical sensors; innovative combined bonding and welding, which saves both production time and car weight; and regenerative braking in lift and conveyor systems to reduce energy costs.

Despite relatively high wages, long vacations, and strong labor laws and regulations, Germany remains a global leader in many manufacturing sectors. Last year, automotive and industrial exports helped the country post a record trade surplus of 198.9 billion euros ($269 billion). One reason: automation. Contemporary German auto manufacturing exploits advanced manufacturing technologies to increase productivity and profits. As a result, manufacturing employment has dropped. Between 1970 and 2012, the proportion of German employment in manufacturing fell by half, to around 20 percent (nearly double the U.S. share).

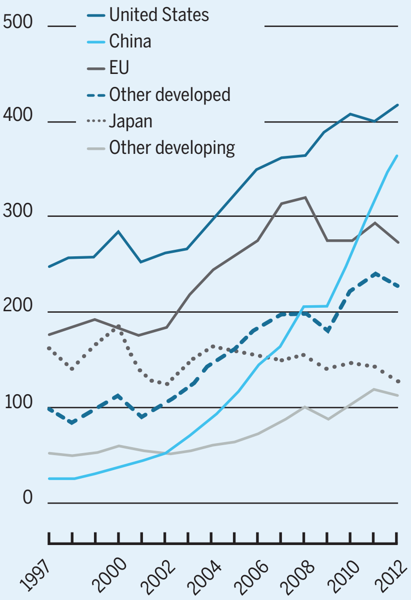
At Audi's A3 body shop in Ingolstadt, the robots are roughly equal in number to the 800 employees.

At Audi's A3 body shop in Ingolstadt, the robots are roughly equal in number to the 800 employees. They do most of the heavy lifting, as well as potentially dangerous spot welding and bonding, and tediously repetitive testing. To Bernd Mlekusch, head of technology development production at Audi, the benefits of automation include much higher productivity and reduced demand for untrained workers. At the same time, workers with more training and greater specialization are increasingly needed, he says. German automotive workers, and German manufacturing workers in general, are already paid significantly more than their American counterparts.

The INTA and group framer machines at Audi exemplify the shift toward automation. INTA, or Ingolstadt *automatisierter Anbau*, is a fully automated door-assembly process that uses an array of sensors, robotic arms, and lifts. As an A3 body is lowered into place, a →

World Order

High-tech manufacturing output (in billions of U.S. dollars)



sensor determines which version of the car—two- or four-door—is coming down the line. A set of robotic arms then fits hinges to the body while another set picks out the correct doors and prepares to mount those to the hinges. Until 2012, this was done manually, says Carsten Fischer, who is responsible for add-on parts, such as doors, at the plant.

The group framer, which does its work in the middle of the body-assembly process, is less ballet and more brawn. It attaches the large structures, like the sidewall frames, to build what we'd all recognize as the body of a car. In a few seconds, roughly 80 spot welds are made by nine robotic arms moving in and around an 18-ton metal contraption that holds the various parts together. The group framer does this without any human intervention and, because of the use of sensors and components that adjust automatically, can switch between as many as three different car models on the fly as they come down the line.

Audi works with KUKA, a leading industrial-robot maker based 84 kilometers away in Augsburg, which in turn works with the Fraunhofer Society, a group of over 60 applied research institutes, jointly funded by industry and the government, whose goal is to facilitate the sort of forward-looking research that a small or medium-sized company might not be able to fund on its own. The innovations that come out of Fraunhofer projects filter back through the whole industry, and experts credit this network of small and large companies and public-private research groups with helping German manufacturing thrive in an era of intense global competition.

The relationships spur innovation but, importantly, also help solidify standards necessary for those innovations to be widely adopted, explains Andreas Müller, who manages RFID technology at Bosch, another company involved in automating factories.

One project Bosch is working on is a German government initiative to use sensors and software to create even smarter factories. The idea is to take the automation in individual processes at a place like Audi's factory and extend it so that every shipping box, component, and manufacturing station will log and share data, Müller says. Today's highly automated factories share data mainly within a single process or on a single factory floor—say, between a machine that scans a car to determine its body type and a second machine that selects a tool of the right size for that body type. The government initiative aims to go much further.

The vision is that data from every step of production will not simply pass from one shop to another within a business—such as from Audi's body shop to its paint shop—but will eventually transit between different partnering companies, optimizing the production process without human input by altering speeds, predicting which components are likely to have been damaged during shipping or tooling, changing the order in which items are built, and reordering parts from suppliers.

Audi's cars are not entirely built by computers and robots, of course. As I pass by an area where people attach mudguards, rear fenders, and a few other parts, one of the engineers chaperoning my visit explains that some stages of physical production are still worker-intensive, whether because of the size or location of the parts involved or the need to perform certain tasks with a precision that robots aren't currently able to achieve. So far the robots can't do these specialized jobs, the engineer explains, but, he adds, "we're working on it." —*Russ Juskalian*

Audi's Hubert Hartmann calls it the most modern factory floor of its kind: "It is like a Swiss watch, with the same level of precision."

SOURCE: NATIONAL SCIENCE FOUNDATION/IHS GLOBAL INSIGHT; COURTESY OF RUSS JUSKALIAN

Robotics

How Human-Robot Teamwork Will Upend Manufacturing

Robots are starting to collaborate with human workers in factories, offering greater efficiency and flexibility.

● Sometime in the next couple of years, if everything goes to plan, workers at BMW's manufacturing plant in Spartanburg, South Carolina, will be introduced to an unusual new teammate—a robot arm that will roll around handing them tools and parts as they assemble the German carmaker's luxury vehicles.

Once isolated behind safety fences, robots have already become safe and smart enough to work alongside people on a few manufacturing production lines. By taking over tiresome and repetitive tasks, these robots are replacing some

people. But in many situations they are augmenting the abilities of human workers—freeing them to do tasks that require manual dexterity and ingenuity rather than extreme precision and stamina. These robots are also increasing productivity for manufacturers and giving them new flexibility.

BMW introduced robots to its human production line at Spartanburg in September 2013. The robots, made by a Danish company called Universal Robots, are relatively slow and lightweight, which makes them safer to work around. On the production line they roll a layer of protective foil over electronics on the inside of a door, a task that could cause workers repetitive strain injury when done by hand, says Richard Morris, vice president of assembly at the Spartanburg plant. Existing industrial robots could perform this work, and do it much more quickly, but they could not easily be slotted into a human production line because they are complicated to program and set up, and they are dangerous to be around.

While the prospect of increased automation will inevitably cause worries about disappearing jobs, BMW's Morris can't foresee a day when robots will replace humans entirely on the factory floor. "Ideas come from people, and a robot is never going to replace that," he says.

Still, robots on human production lines at BMW and other manufacturers promise to transform the division of labor between people and machines as it has existed for the past 50 years. The more traditional robots that apply paint to cars, for example, work with awesome speed, precision, and power, but they aren't meant to operate with anyone nearby. The cost of setting up and programming these robots has helped ensure that plenty of small-batch manufacturing work is still done by hand. The new robots, with their ability to work safely next to human coworkers, let manufacturers automate parts of the production process that otherwise would be too expensive. And eventually, by collaborating with human workers, the robots will provide a way to combine the benefits of automation with those of human ingenuity and handcraft.

Sales of Universal's robot arms have grown steadily since they first came to market in 2008. Other companies, such as Boston-based Rethink Robotics, are developing similar robotic systems designed to work close to people. Rethink sells a two-armed robot called Baxter that is not only safe but extremely easy to program; any worker can teach it to perform a new task simply by moving its arms through the necessary steps.

The next generation of robots to work alongside humans are likely to be faster and more powerful, making them considerably more useful—but also necessitating more sophisticated safety systems. These safeguards are now affordable because the sensors and computer power needed to react quickly and intelligently to safety risks have become cheap. In the future robots will also collaborate with humans in far more complicated ways—performing the heavy lifting in an installation job, for example, while the human does the necessary wiring.

BMW is developing its next generation of robots in collaboration with the lab of Julie Shah, an assistant professor at MIT who researches human-machine collaboration. The lab is also working with the aircraft makers Boeing and Embraer. "If you can develop a robot that's capable of integrating into the human part of the factory—if it just has a little bit of decision-making ability, a little bit of flexibility—that opens up a new type of manufacturing process more generally," Shah says.

85%
Reduction in workers' idle time when they collaborate with robots

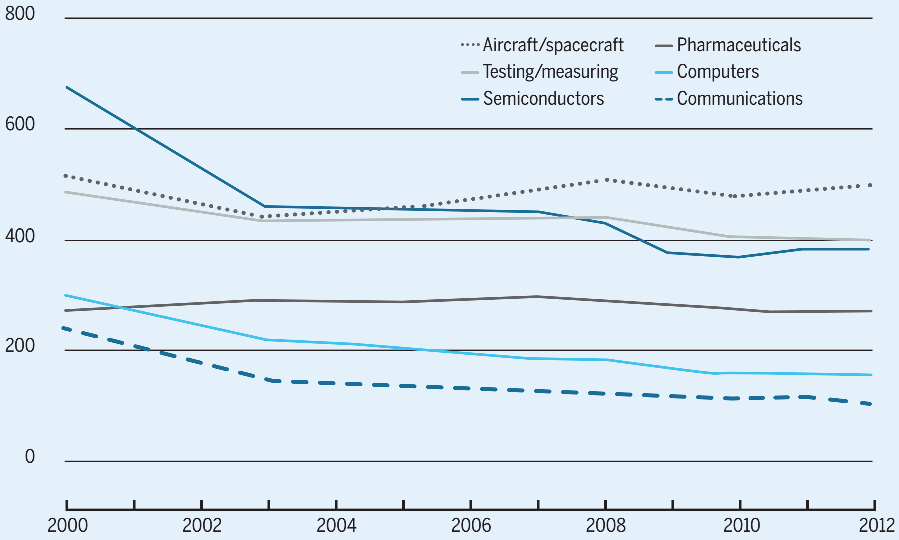
Shah is developing ways for robots to interact intelligently with their human coworkers. At ABB, a Swiss energy and automation company, human and robot teammates swap tasks to learn each other's preferences, resulting in a process that gets the job done more quickly. Shah has also shown that teams made of humans and robots collaborating efficiently can be more productive than teams made of either humans or robots alone. In her experiments, this coöperative process reduced human idle time by 85 percent.

Workers seem comfortable with the idea of robotic colleagues, too. The latest research from Shah's lab, in fact, suggests that people collaborating with manufacturing robots prefer to let the robot take the lead and tell the workers what to do next. So the robots on the production line in Spartanburg might someday be upgraded from handing out tools to giving instructions on how to use them.

—Will Knight

High-Tech Factory Jobs

U.S. employment in high-tech manufacturing industries (in thousands)



SOURCE: NATIONAL SCIENCE FOUNDATION/BUREAU OF LABOR STATISTICS

Jobs

The Hunt for Qualified Workers

Employers have 300,000 unfilled manufacturing jobs.

● Worried that U.S. workers are ill-prepared to work with new manufacturing technologies like 3-D printing and robotics, President Barack Obama has plans for a national program that over the next 10 years would build 45 hubs where manufacturing companies, community colleges, universities, and government agencies can prepare workers for the factories of the future.

The program underlines a growing concern that gaps in workers' skills will hinder the current renaissance of American manufacturing. Although employment in the U.S. manufacturing sector dropped steadily from 2000 to 2010, manufacturing has added 646,000 net new jobs over the past four years, according to White House figures.

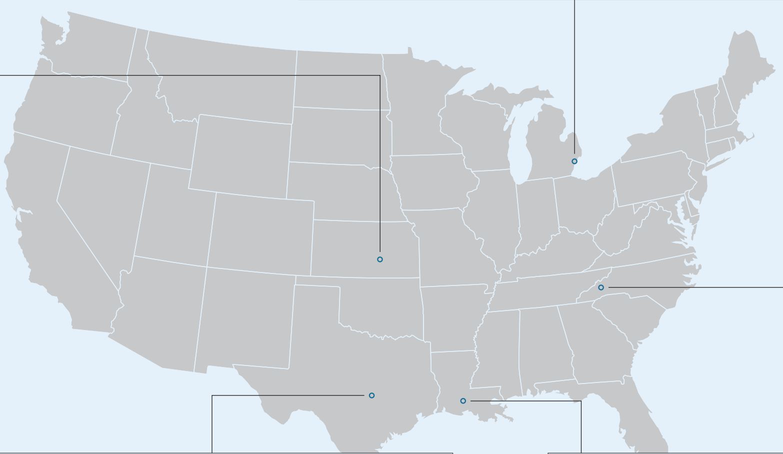
Though many firms are hiring, as of late June, 302,000 manufacturing job openings were unfilled, according to the U.S. Bureau of Labor Statistics. A skills shortage could grow more acute in the next few years. The Boston Consulting Group predicts that by 2020, the United States could face a shortfall of 875,000 highly skilled welders, machinists, machine mechanics, and industrial engineers.

The skills gap seems to be confined to a minority of smaller companies that require specialized skills, according to a 2013 report by MIT's Production in the Innovation Economy study. The problem is not as pervasive as one might think given how much attention it has received, says Paul Osterman, a professor at MIT's Sloan School of Management and a member of the commission that conducted the study.

Many of the specialized jobs that manufacturers are having the hardest time filling today involve conventional manu-

Five of the Hardest Manufacturing Jobs to Fill

We compared a list of hard-to-fill jobs from the Manufacturing Institute with a proprietary labor-market data set from Economic Modeling Specialists International, which pulls pay rates and other data from industry and government sources. Manufacturers listed are a sampling of major employers in the metro area where each job is most concentrated.

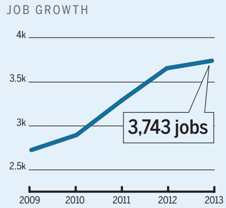


MECHANICAL ENGINEERING TECHNICIAN | Detroit

Calibrates, tests, and modifies machinery

WORKERS 45 AND OLDER: 52%
HOURLY EARNINGS: $27.33

LOCAL MANUFACTURERS
Ford, LHP Software, Mahindra Engineering

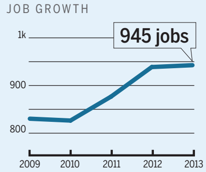


CNC MACHINE TOOL OPERATOR | Asheville, NC

Controls machines that make metal-on-plastic parts

WORKERS 45 AND OLDER: 48%
HOURLY EARNINGS: $18.39

LOCAL MANUFACTURERS
BorgWarner Turbo Systems, Kearfott Corporation, GE Aviation

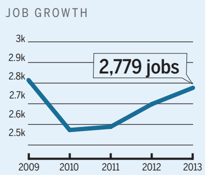


MACHINIST | Wichita, KS

Operates tools to make or modify precision parts

WORKERS 45 AND OLDER: 61%
HOURLY EARNINGS: $18.29

LOCAL MANUFACTURERS
Spirit AeroSystems, Textron Aviation, Bombardier Learjet

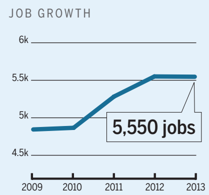


ELECTRONICS ASSEMBLER | Austin–Round Rock, TX

Assembles or modifies electronics equipment

WORKERS 45 AND OLDER: 47%
HOURLY EARNINGS: $12.08

LOCAL MANUFACTURERS
National Oilwell Varco, AirBorn, 3M

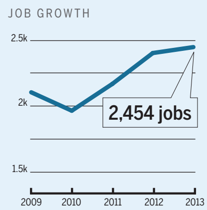


WELDER | Lafayette, LA

Joins metal parts by soldering, welding, brazing, and cutting

WORKERS 45 AND OLDER: 34%
HOURLY EARNINGS: $17.99

LOCAL MANUFACTURERS
Exterran, Frank's International, Allison Marine



SOURCES: THE MANUFACTURING INSTITUTE, ECONOMIC MODELING SPECIALISTS INTERNATIONAL, U.S. BUREAU OF LABOR STATISTICS, U.S. CENSUS BUREAU

facturing tasks. Pipe fitters, mechanical engineering technicians, welders, machinists, electronics assemblers, and operators of computer-numeric-controlled machines are among the most needed workers identified in surveys conducted by the Manufacturing Institute, a nonprofit research affiliate of the Washington, D.C.–based trade association the National Association of Manufacturers.

As workers retire, it's becoming harder to find people with these traditional skills, says Ben Dollar, a principal in Deloitte Consulting's manufacturing practice.

For a smaller number of companies, the priority is getting workers up to speed on the skills they'll need in tomorrow's factories. In the last 18 months Siemens USA has donated more than $3 billion worth of manufacturing software to colleges in a bid to help train the next generation of advanced manufacturing workers.

Siemens itself plans to hire 7,000 more people in the U.S. by 2020. Their positions will be related to IT, software development, software engineering, and computer science, says Siemens USA CEO Eric Spiegel. "The digital world is coming, and it's coming very fast," he says. "There will be jobs. People may not count those jobs in IT and software development as manufacturing jobs, but they really are related to manufacturing."

—*Kristin Majcher*

Case Study

The New Chinese Factory

Leading manufacturers in China combine the country's historical labor advantages with expertise in automation, design, and manufacturing.

● With its medieval canals and carefully preserved downtown, the eastern Chinese city of Suzhou might have been a quiet burgh compared with neighboring Shanghai. But in 1994, the governments of Singapore and China invested in an industrial development zone there, and Suzhou grew quickly into a manufacturing boomtown.

Singapore-based Flextronics, one of the largest global contract manufacturers, built factories there, initially to make small consumer electronics. Those products were relatively simple to assemble in great numbers, making them well suited to China's then plentiful and inexpensive labor force. But by 2006, labor, land costs, and competition were rising, and Flextronics' margins were shrinking.

$600 billion

Value of Chinese high-tech exports

The company refocused its two Suzhou factories on more complex manufacturing, aiming to make higher-priced machines for the aerospace, robotics, automotive, and medical industries. To do so, Flextronics has invested in automation, increasingly precise manufacturing, and improved worker training, all while learning to manage a complicated component supply chain.

Today, these more complex goods make up 72 percent of Flextronics' Suzhou output. Finished products include printed circuit boards, hospital ultrasound machines, and semiconductor testing equipment so complex each machine requires more than five million parts and retails for $2 to $3 million.

It's a model the Chinese government has pushed manufacturers to adopt, focusing government investment on advanced industries and boosting R&D spending on science and technology. According to data from the U.S. National Science Foundation, between 2003 and 2012 Chinese exports of high-tech products climbed from just over $150 billion to more than $600 billion, making China the largest exporter of such products in the world. Ernst & Young forecasts that by 2022, the country will produce a third of the world's electrical goods.

On a recent visit to one of Flextronics' two Suzhou plants, the increasing use of automation is quickly apparent as an automated trolley delivers parts to workers up and down an assembly line, stopping if someone crosses its path. Nearby an LCD wall panel shows the progress of various items moving through quality testing. In the past, workers ticked off boxes on paper forms and entered the results into computer spreadsheets—a time-consuming process fraught with the potential for errors. Now automated data about progress down the assembly line is collected in real time.

Clients can track the data on apps designed by Flextronics. When there's a disruption due to anything from delivery problems to labor strikes, another app, Elementum, taps into the extensive Yangtze Delta region supply chain, showing customers alternate scenarios for sourcing parts or rerouting production to any of the company's 30 other mainland plants.

Such services are part of Flextronics' push to show customers that after years making goods to the specifications of demanding customers like General Electric and Philips, it has more to contribute. Today Flextronics offers its own design and engineering services, consulting on both finished products and ways to improve the manufacturing process.

Flextronics has sometimes expanded its high-end work by going into business with customers. About four years ago, Steven Yang, general manager of one Suzhou factory, led a company investment in a French firm designing a small robot to be used for university research and, potentially, therapy for children with autism. Working from their prototypes, Flextronics designed a manufacturing process that has in six months delivered 1,400 of the robots, which use sonar and facial recognition technology and can be programmed to listen and to speak.

James She, an operation manager in charge of the robot line, says volume has more than doubled since the initial run in the final quarter of 2013, and he expects orders to rise, especially in Asia, where health care and elder care are fast-growing industries. "The robot can be a member of a family in the future," She says.

Flextronics has pursued automation wherever it has the potential to reduce labor costs and errors. For example, automated optical testing equipment, ⟶

which checks that the circuitry on printed circuit boards is correct before they are installed in other machines, has cut the number of workers on the inspection line from six to two.

But as product cycles speed up, it doesn't always make sense to make large investments in robots. Humans are still more flexible. "The time you have to spend changing the machine means it's not always worthwhile to automate," says Es Khor, an engineering director at the factory. "When we look for where to automate, we also look for process-specific, rather than just product-specific, tasks."

So while the French robot line may be creating the health-care assistants of the future, at the moment the robots are being assembled by 28 workers wearing navy blue uniform smocks, mostly young men from rural China. All of them have had at least three months of technical training, and the French company provides performance-based bonuses and organized leisure activities in hopes of reducing turnover and retraining costs. Flextronics has also upgraded its dormitories, built worker break rooms, organized hiking trips and choral groups for employees, and staffed counseling hotlines, all with a view to retaining increasingly expensive, and highly trained, labor.

Twenty-year-old Lan Wenzhi has been working on the robot production line for six months. His job is fastening in tiny screws that hold the battery inside a small box. He has a high school diploma, a smartphone, and a fondness for American movies. His monthly average take-home pay after taxes, including overtime, is about 3,500 yuan (about $570). Factory general manager Yang says that with rising wages in this part of China, labor has increased from about 2 percent of the factories' costs in 2005 to about 4 percent today. But it's still relatively small when compared with the 80 to 85 percent of the operating budget spent on materials.

For Yang and Flextronics, the goal is to take advantage of nearly two decades of manufacturing experience to make their factories centerpieces of innovation, not just cheap places to make things.

—Christina Larson

Economics

Cheap Natural Gas Boosts Manufacturing

Companies that use natural gas as a raw material find the U.S. an increasingly attractive place to be.

● The fastest-growing slice of the U.S. manufacturing sector today is not being driven by automation or cutting-edge robotics but instead by cheap, plentiful natural gas unleashed by fracking shale deposits.

From 2011 to August 2014, the American Chemistry Council, the trade association of the chemical industry, tallied 196 announcements of new chemical plants or upgrades to existing ones in the United States, with investments totaling $124 billion. Huge petrochemical companies such as Saudi Basic Industries, Dow Chemical, and Chevron Phillips Chemical Company are among the investors. Texas is undergoing the largest expansion of petrochemical manufacturing since the 1960s, and other gas-rich parts of the country, including Pennsylvania and the Ohio Valley, are benefiting too.

"Ten years ago everyone was talking about projects in the Middle East," says Fernando Musa, CEO of Braskem America, a Philadelphia-based subsidiary of the Brazilian thermoplastic resin leader. "Now if you go to industry forums in the U.S., Europe, or Asia, everyone is talking about investing here in the U.S."

Many of these investments are from companies that use natural gas instead of petroleum as a raw material, such as the large petrochemical producers. But cheap natural gas is also offering the prospect of lower electricity costs, which gains the attention of a broad spectrum of manufacturing. The U.S. Conference of Mayors expects employment in energy-intensive manufacturing to grow 1 percent a year through 2020. Steelmaker Nucor has opened a plant in Louisiana that will use natural gas to strip oxygen from iron ore, a classic manufacturing technique that, before the shale boom, had been too expensive for the company to do in the U.S. Tire companies that had largely moved manufacturing to China in recent decades have now announced eight new U.S. plants, including new Bridgestone and Michelin facilities in South Carolina.

U.S. manufacturers could see their energy costs drop by more than $20 billion a year by 2030, according to consulting firm PwC. That could benefit electricity-intensive advanced manufacturing plants, but for many advanced manufacturing facilities the potential savings from cheap electricity are secondary to other considerations.

Samsung Electronics, which operates semiconductor fabrication plants in Austin, Texas, pays close to $60 million a year in electrical bills, says general counsel Catherine Morse, but its recent decision to invest $4 billion mostly in new tooling at the site had nothing to do with electricity prices. Its energy supplier, Austin Energy, relies extensively on solar and wind power, so cheaper gas has a limited benefit for Samsung.

The investment was primarily motivated by an interest in expanding the existing plant's expertise in logic chips, the chips that control the operation of digital devices. "We do benefit from lower natural-gas prices," says Morse. "But that's not driving our investment."

—Nanette Byrnes

For a photographic tour of Audi's high-tech plant, plus stories on 3-D printing, manufacturing in California, and more, please go to technologyreview.com/business.

Mummified deer leg, sealed in beeswax.

Reviews

Fun with Food

Playful new cooking based on traditional methods and weird ingredients will supplant the industrial techniques that dominated modernist cuisine.

By Corby Kummer

Ever since cooks began playing with the equipment of the food industry, chefs have felt compelled to join one of two camps. The first believes any kitchen is incomplete without a centrifuge, combination steam-convection oven, and $6,000 vacuum-seal machine and immersion circulator to cook 22-hour eggs *sous vide*. The second camp takes pride in telling you that all these gadgets, and ingredients like hydrocolloids and calcium baths, are outlawed in *their* kitchens—because gadgets and industrial powders have nothing to do with cooking. But now that the equipment, ideas, and techniques of modernist cuisine have been around more than a decade, a new generation of chefs declines to declare loyalty to either camp. To me, the most interesting cooks today are not on the barricades but those eager to discover new flavors. They use low-tech means like fermentation and cook over a stove.

The really ambitious cooks—those who aspire to a place on the world culinary map—create those novel flavors at food labs.

Until now, the two chefs most associated with labs are linked to modernist cuisine: Heston Blumenthal, at the Fat Duck, in Berkshire, England, and Ferran Adrià, who was chef at the most famous modernist restaurant of all, El Bulli in Catalonia, Spain, and who chaired the advisory board of the Basque Culinary Center. Both labs were something more than test kitchens: they were places to try new techniques. The results found their way into new restaurants, books, and a study center and (in the case of the Basque Culinary Center) were shared with the industrial clients that subsidized the enterprise.

The closest counterpart to these men in the United States is David Chang, a hero to younger American cooks. His Momofuku Group of restaurants subsidizes a separately staffed "culinary lab," whose goal is to discover new components. Chang and his cooks collaborate with mycobiologists and engineers at MIT, Harvard, and Yale; the purpose of that collaboration, in the words of Ryan Miller, product development chef at the lab, is to bridge the gap between "the way a cook learns something, which is visual and tactile," and a "conceptual understanding" of, say, the enzymatic microbial processes that make soy sauce or miso.

Nordic Food Lab

Noma
Copenhagen, Denmark

Non-Nomative cooking

Then there is the Nordic Food Lab, which can be found in a houseboat on a Copenhagen canal, a short walk down a cobbled lane from a restaurant called Noma. The lab is the brainchild of Rene Redzepi, whose quest at Noma for new flavors, whether from plants, fungi, lichen, or animal by-products, has given rise to an international obsession with foraging for new, questionably edible ingredients. It's easy to parody the results. But up close, in the sweeping, palatial kitchens of Noma, a floor above the restaurant, the patience, attention, and meticulous care with which gnarled and ancient vegetables or half-rotten weeds are treated is impressive, as is the dedication of the international cast of apprentices who vie for a spot to *stage*. A typical late afternoon might find *stagiaires* carefully lifting the skin off a highly concentrated duck stock—ordinarily a bubbly gray-white scum, but here a shimmering golden-brown sheet, gleaming like mica—and topping it with home-pickled beech leaves, to be seasoned with a lacto-fermented plum.

The lab is more freewheeling and less quiet. It, too, attracts young people from around the world. But music blares as they work at laptops on one of two trestle tables, or at the counters and stove. (Unlike other labs, which often have only induction burners, this one includes an actual, working stove.) The young people are as likely to hold advanced degrees in biomedical science, flavor chemistry, and geography as they are to be cooks. They want to make and grind koji, the fermented-rice base of sake, to use as a chocolate surrogate for a cake; or anaerobically ferment plums individually encased in a lustrous, thick shell of beeswax; or mummify a deer leg to see if it will taste like Parma ham; or ferment grasshoppers into a version of garum, the gamy fish sauce of the ancients; or whip pig's blood to mimic the foam structure of egg yolks for an ice cream that looks and tastes like chocolate (blood cooks to the same shade of brown).

Koji-chovies—herring made in the style of anchovies.

From top, clockwise: a day of experiments in the window; a "chimp stick": licorice root, whittled down and brushed with juniper-wood-infused honey, and stuck with herbs, seeds, nuts, fruits, and two types of ants; and a buckwheat pancake with desert locust, pickled beet, and fresh cheese.

OPPOSITE: COURTESY OF CLAES BECH-POULSEN; CLOCKWISE FROM TOP: COURTESY OF CLAES BECH-POULSEN; COURTESY OF NORWEGIAN AIR; COURTESY OF CHRIS TONNENSEN

The houseboat's continuous, slight rocking plays hell with meticulous measurements or the maneuvers required to lift the fragile skin off a stock. Yet this is where the cool kids come to rock before jetting off to the Amazon or the plains of Uganda to collect bee larvae or salamander-size crickets.

It's easy to assume that the lab is a test kitchen for Noma. It was, after all, started by Redzepi (along with Claus Meyer, a high-profile food entrepreneur in Denmark, who was also a partner in the restaurant); it's a very few steps from the houseboat to the back stairway up to the Noma kitchens; and daily foot traffic flows between the restaurant's office and kitchen and the lab.

But the two are separate ventures. The lab is a nonprofit organization and gets no funding at all from Noma. The initial money came from the Danish government and the innovation fund of Nordea, a Stockholm-based financial services group. Now the director, Michael Bom Frøst, a professor of sensory sciences at the University of Copenhagen, regularly applies for grants to foundations, universities, corporations, government entities, and the European Union to maintain its budget.

Such funding is one reason for the Nordic Food Lab's recent concentration on insects, the subject of almost all the publicity about the lab. An interest in insects is not the result of any core founding principle—Redzepi's original mission was just the "scientific identification and exploration of deliciousness." It's a consequence of the largest grant the lab has received to date: $655,000 from the Swiss-based Velux foundation, which funds technical and basic scientific research, to explore "deliciousness as an argument for entomophagy." Insects are, of course, the miracle protein of the future: no one asking how we will feed the world can avoid talking about them. Nor, if you go to a trendy restaurant, can you escape being offered a grasshopper taco or a cricket-covered chanterelle bavarian. From the fall of 2013 to the fall of 2014, that money sent Ben Reade, once an intern at the lab who became head of culinary R&D, and Josh Evans, a Yale grad who is one of the lab's three paid full-time employees, to Kenya, Uganda, the Australian outback, Mexico, Peru, and Sardinia, as well as the Netherlands and northern Denmark, to find and film grasshoppers, beetles, bees, crickets, and other insects that have served as food.

Reade and Evans have gotten very good at tossing off aperçus like "Bee larvae could be the caviar of insects" and "Exoskeletons can be useful for crunch—for instance, in a roasted grasshopper." The team at the lab happily spends days developing granola with bee larvae and honey on oats and various seeds. Bee larvae, Evans notes enthusiastically, are half protein and 20 percent mono- and polyunsaturated fat (the good kind), with "loads of vitamins and minerals." And insects might be genetically modified to be even higher in protein and what are thought to be beneficial lipids.

But the lab isn't an uncritical cheerleader for such ideas. Reade is wary of insects as the "next moneymaking scheme" for protein: "never a good thing for biodiversity and food security," he says. He's skeptical that people who have never eaten them before will enjoy them. The immediate agricultural future of insects is in animal feed: such a diet is certainly better suited for chickens, who peck at insects, than the fish meal they're given now. The lab wants to explore and refine traditional foodways, he says, not change cultures.

Nebulized benefits

On any day the small staff and cadre of interns will be working on other projects, both funded and unfunded. The main tool in the lab is not the refractometer, the thermometer, or the digital scales and other measuring instruments. (The lab no longer possesses that symbol of the truly lavish kitchen, a centrifuge.) Instead, the team wields a "spice rack of microbes"

COURTESY OF CHRIS TONNENSEN; COURTESY OF CLAES BECH-POULSEN

From left to right: beeswax ice cream, freeze-dried honey crisp, honey kombucha sauce, and fermented pollen; umami sauces fermenting in a thermobox; venison loin cured with seaweed and lichen; Josh Evans.

COURTESY OF CHRIS TONNENSEN; COURTESY OF LINE KLEIN

to ferment every kind of grain and fruit. The results appear in the grasshopper garum, that surrogate chocolate cake, and the food-friendly beers that, along with insects, are the main funded project at the lab.

On behalf of the huge Danish brewery Carlsberg's craft brewer, Jacobsen, the lab is experimenting with various forms of kombucha (black tea fermented with bacteria and yeast) and with a longtime obsession, koji—rice fermented with the aid of *Aspergillus oryzae*, the national fungus of Japan. The lab has used koji to create a wide range of flavors; there are dozens of samples fermenting in a refrigerator downstairs, with bases of wheat, barley, and little-used northern-climate grains. (A small broom closet off the bathroom was the researchers' "mold room" until the molds proliferated, and the landlord killed months of labor and replaced the walls' surfaces.) Carlsberg wants to develop a line of beers that will win the respect of sommeliers who must pair brews with courses; the lab is using strains of *Aspergillus* to ferment various raw ingredients, and roasting koji to give malty, chocolatey flavors to new craft beers.

The most rewarding projects might be the unfunded ones that draw on the researchers' passions, which reflect Redzepi principles: going into a field, kicking an anthill, using pieces of bread to absorb the formic acid ants emit, and using that to add lemony notes to a stew—a trick they learned from a longtime forager. Or walking into the woods with alcohol and sample bottles to make tinctures that can much later be combined in a sweet or savory dish based on the principles of perfumers—an interest of Reade, who read about the oak moss and peach base of one of the 20th century's most enduring fragrances, Mitsuoko, and sprayed nebulized spruce tincture over a granita of peach juice, crystallized peach skins, and sheep's-milk frozen yogurt, accompanied by crispy oak moss, to make what he calls a "magical, ethereal dessert."

Much of this is play, blending science and cooking techniques with anthropology, sociology, and cultural history. It is a kind of experimentation that has already made a lasting impact on the new generations of chefs—cooks like Sasu Laukkonen, a Finnish chef who was one of hundreds to gather for MAD, Noma's annual August chefs' jamboree, held in a tent on a far Copenhagen canal. Recently, he was eating in the vast new Amass, a restaurant opened by Matt Orlando, a San Diego–raised chef who ran the kitchens at Noma and is one of several graduates to open restaurants in Copenhagen. "Cooking in plastic bags is over," he announced as Orlando came to say hello. "It's come and it's gone." Orlando nodded and said that not only is Amass *sous vide* free but "there will never be meat glue in my kitchen." Whatever equipment fads come and go, chefs will always be in search of new flavors based on nature. It is to find those flavors that the Nordic Food Lab was established.

Before MAD, Reade decided to make haggis using a basketball-size sheep's rumen he had carried to Copenhagen from a farm in his native Scotland; as a Scots friend played the bagpipes, it would be borne in by a kilted Reade with somber ceremony at the finale of the conference, whose theme was "guts." (Reade has since returned to Scotland to help activate a national chapter of Slow Food.) One late afternoon, following a day of checking on *Aspergillae* and the mummified deer leg, he was hand-chopping sheep's heart, lung, stomach, liver, kidney, tongue, and suet and blending the result with oats, foraged herbs, and a good dousing of whiskey before stuffing it all into the heavy, enormous rumen, which had to be lifted into a pot—an all-hands-on-deck process that left everyone smelling strongly of sheep offal.

The remedy? Strip and dive into the canal—not an uncommon end to a day's research on a Copenhagen houseboat.

Corby Kummer is an editor at the Atlantic *and restaurant critic at* Boston *magazine.*

Confessional in the Palm of Your Hand

Sure, people say some nasty things in anonymous apps, but the good far outweighs the bad.

By Rachel Metz

"I want to quit Google," the message on my iPhone read. "It's boring here."

Posted by an anonymous user in San Francisco to the confessional app Secret, the message quickly gained attention; after four days, it had received 78 comments, ranging from "just means you're not on the right project" to "I quit Google, and it was one of the best decisions of my life." At times, the original poster chimed in, saying things like: "I've been there a long time. Many jobs. The company no longer values initiative, and promotion is very slow."

Many of us are addicted to sharing status updates on Facebook, photos on Instagram, and thoughts on Twitter. But real, raw honesty is tricky online. It's hard to say what you really think when your true identity is attached, especially if your post could get you in trouble, either now or years down the line. That bored Googler on Secret wouldn't be likely to voice those thoughts online under his or her real name—even if doing so could be therapeutic or even lead to other job options.

That's why anonymous social apps like Whisper and Secret come as a relief. Yes, anonymity and self-disguise have always been available on the Web, from early chat rooms to newspaper and blog comment sections to the darkest corners of 4chan. And yes, commenters have often used that cloak of anonymity to say things that are meaner than anything they'd have the guts to say to someone's face.

Here, though, the combination of anonymity, the simplicity of a focused app, and the intimacy of a smartphone screen makes sharing your deepest, darkest thoughts and commenting on others' strangely satisfying. The more I used these apps to confide, the more it felt like having a tiny confessional in the palm of my hand. Occasional trolls be damned, I got hooked on the rush of comments and likes that came with a juicy confession. Even if the people on the other end didn't really know me, I felt that I could be honest with them and get real sympathy.

Drinking with Strangers

With Whisper, sharing is easy: you type whatever you want and the app suggests a photo based on your message—often one that doesn't quite match the topic. Other people's posts show up with several lines of bold text and an image, risking sensory overload. Scrolling through Whisper is like looking at snippets from countless strangers' diary entries, only here you're encouraged to respond.

Posts are visible to anyone using the app, and many of the more popular ones are searingly honest. On a recent day, a quick look yielded "I just found out my boyfriend was born a girl"; "My son is offi-

MAXIMILIAN BODE

cially older than my boyfriend"; and "It makes me sad when I see my two year old pretend to inject meds into her stomach to be like her mommy. Fuck diabetes!" People do respond sympathetically to all kinds of posts—everything from one user's admission that he or she cries about little things like when there's no milk left in the fridge to another's lament about people being unaccepting of homosexuality.

One person suffering from depression had finally started seeing a therapist and taking medication. It was warming to see that post elicit encouragement.

Still, I preferred Secret, which looks simpler and sticks to a smaller social circle. The app has two tabs. One shows secrets from your friends and friends of friends (though you can't see who these people actually are—the app matches you with your social network by looking at the contacts on your phone and finding those who are using Secret). The other tab displays secrets from people who are nearby and posts that Secret has decided to show you for reasons that aren't made clear.

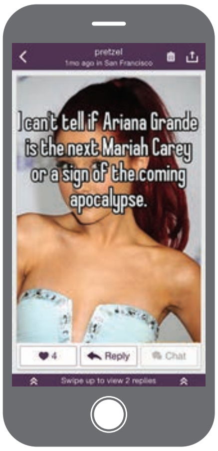
You can comment only on the posts made by friends or friends of friends and on certain posts rolling in from those near you. This gives Secret an intimate feel. Rather than displaying usernames, Secret denotes the original poster of any given secret with a crown icon; each commenter gets a random icon ranging from a wine glass to what appears to be either a dollop of soft-serve ice cream or a pile of poop.

With fewer choices, Secret feels more sedate than Whisper, and more manageable. When I first tried the app in February, it was brimming with juicy tech-industry gossip, but that seems to have dropped dramatically. Lately, my Secret feed has been humming with posts about love, sex, work, and relationships, such as "I think I'm too selfish now to be in a relationship since I've never been in one and I'm well into my 30s." The recent addition of a polling feature has resulted in lots of annoying yes-or-no questions. (My network includes many Silicon Valley types, which means I see tech-centric questions like "Would you use a social network launched by Yahoo?") There are also serious posts—one person suffering from depression said he or she had finally started seeing a therapist and was taking medication. It was warming to see that post elicit a support-group-like response of congratulations and encouragement.

I was feeling so positive about Secret, especially after hearing that some people were using it to organize dinner parties with strangers, that I decided to see if the good vibes engendered by the app could translate to real life. I posted an invitation to anyone in my extended social network to meet me after work at a cocktail bar in San Francisco's Soma neighborhood. Positive comments poured in, with several folks saying they would attend and others saying they wished they were close enough to pop by.

I arrived at the bar excited to meet my new friends. But after I drank alone for an hour and a half, only one commenter showed up. I wasn't mad at anyone—I had no idea who to be mad at.

But while anonymity can make people unreliable, it can offer some good surprises. My eventual companion told me her real name was Taleen Alexander. After a rough day, she just felt like having a conversation with someone she didn't know. It turned out we had a lot in common: we both grew up in the Bay Area and went to the same college (UC Berkeley), where we majored in the same subject (English). Because it wasn't the kind of thing either of us normally do, and because we'll probably never see each other again, it felt

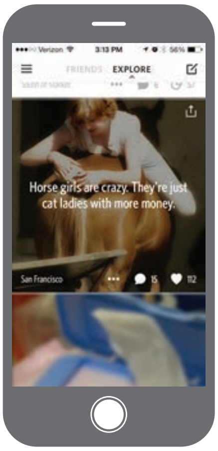


Whisper

Pro: Posts can be displayed by topic or by the poster's distance from you, among other choices.

Con: It can feel like a dumping ground for secrets, with bad fonts and stock photos. A lot of posts are soliciting sex.

Sample revelation: "I gave my little brother and his friends non-alcoholic beer last night. Watching them 'get drunk' was absolutely hilarious."



Secret

Pro: Connects you, anonymously, to people within your social network rather than a universe of strangers.

Con: Diversity of posts can be limited, and there's no way to search by topic.

Sample revelation: "So many white dudes on stage at TechCrunch Disrupt. As a white dude, even I'm offended."

exhilarating to talk about what was really going on in our lives.

The Icky Underbelly

Keeping these apps fun and useful inevitably means fighting with trolls who make nasty comments and issue personal attacks. I didn't find this kind of dreck pervasive, but it's not hard to find, and I can see why parents would be concerned about impressionable teenagers using apps that encourage anonymous interactions. It's much easier to be a jerk when you never have to reveal your identity.

That said, I don't think Secret and Whisper should consider it their responsibility to wear kid gloves when dealing with the under-18 crowd, and they do appear to be working to minimize the bad stuff. Secret urges users to "say something kind" when commenting, and it lets you delete ugly comments responding to one of your posts. I also noticed a fair number of reminders sprinkled throughout the app urging me to "help keep the community safe" by flagging posts that don't adhere to Secret's rules.

When I tried to publish a post with a picture of the singer Ariana Grande, an alert popped up asking whether I was posting about someone, warning me that "defamatory, offensive, or mean-spirited" posts violate Secret's terms and may be deleted. The warning needs work, though: I got the same message when I posted a photo of some delicious marcona almonds.

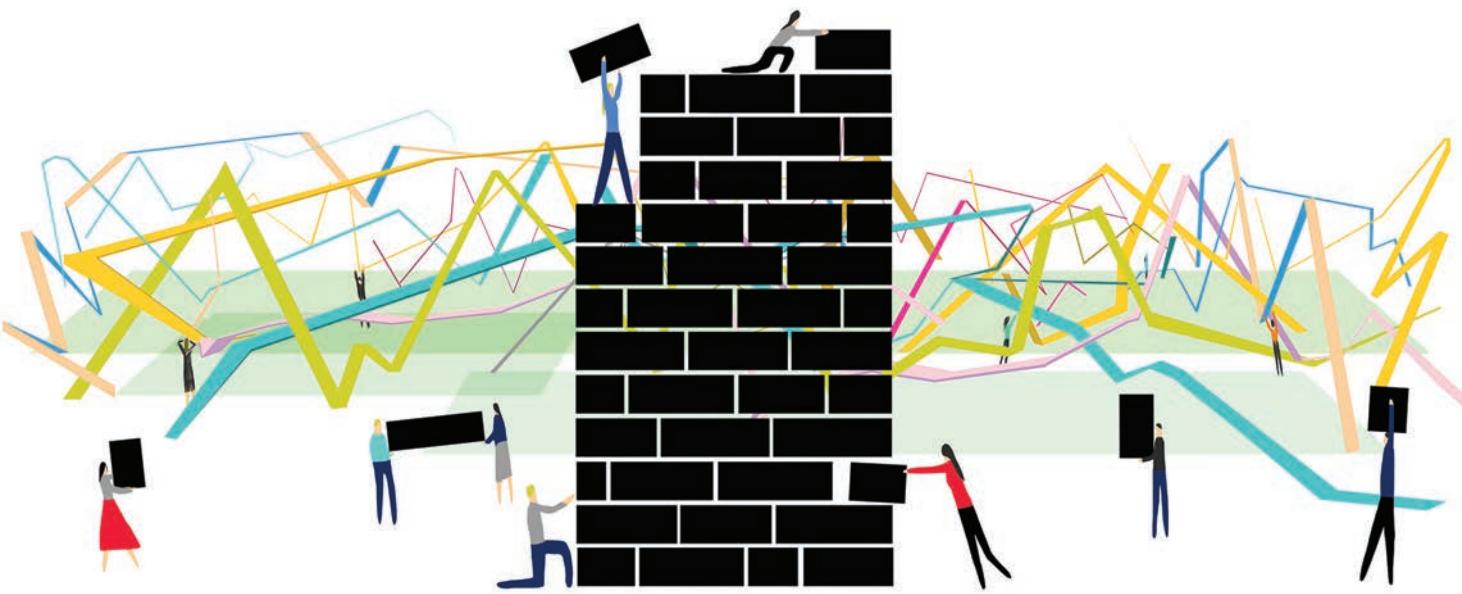
On Whisper, there wasn't such in-your-face emphasis on keeping mean content off the app, but it was easy to call out jerks: an icon at the top of each post lets you flag or hide the post or report a user for bullying, impersonating someone else, or spamming. Whisper also uses both software and people to weed out inappropriate posts and says it doesn't let users write posts with people's real names in them. (I was able to publish one, but it had been deleted by the next morning.)

The efforts appear to be working. Whisper says negative comments and posts make up a "single-digit percentage" of the app's total, which reflects my experience.

But even seeing an occasional ugly comment slip through seems like a small drawback considering the overwhelming number of sincere, reflective, self-deprecating, confused, commiseration-seeking ones. So much of what we say and do online is preserved permanently, and in life offline we still have to watch what we say at work and even around friends and loved ones. Apps like Whisper and Secret let you blow off steam or share your most private thoughts before (or instead of) sharing them in person. Speaking up in these digital spaces can bring out the trolls, but it's often followed by compassion from others, and a sense of freedom and relief.

Anonymity can offer some good surprises. It felt exhilarating to talk about what was really going on in our lives.

Rachel Metz is MIT Technology Review*'s senior editor for mobile.*



JON HAN

The Contrarian's Guide to Changing the World

Investor Peter Thiel has inspiring advice for wanna-be entrepreneurs, but he is unrealistic about where technology really comes from.

By Jon Gertner

Is the technology investor Peter Thiel brilliant, or is he just strange? He is nothing if not industrious. Since he cofounded PayPal, in 1998, Thiel has had a hand in some of the most important and unexpected tech companies of our era. His success has made him an oracular presence in Silicon Valley.

Thiel's contrarianism is notorious, and he appears to delight in saying or doing the unexpected, even at the risk of ridicule. Each year, his nonprofit gives a handful of college students $100,000 to drop out of school and pursue a risky startup. He has declared himself to be not only against taxes but against "the ideology of the inevitability of death." And when the Seasteading Institute—a utopian group intent on building floating cities so as to escape the intrusions of government—sought funding a few years ago, Thiel ponied up half a million dollars.

If one wanted to emulate Peter Thiel's success, would one have to do more than just the opposite of everyone else? His new book—a polished version of some lectures he gave at Stanford for aspiring entrepreneurs in 2012—suggests that there is such a creed as Thielism. His theories on what makes a good technology company and how such companies can improve society are by turns brazen, thoughtful, and precise; the challenge lies in separating the truth from the truthiness. Thiel insightfully diagnoses the failings of today's technology (see Q&A, page 24), but the cures he suggests are questionable.

Zero to One
By Peter Thiel with Blake Masters
Crown Business, 2014

According to Thiel, most startups funded by his fellow Silicon Valley investors shouldn't exist. All prospective entrepreneurs, he suggests, should ask themselves a simple and essential question: "What valuable company is nobody building?" If they don't have an answer, they should do something else.

You see, Thiel is not interested in funding entrepreneurs trying to build a business that will beat the competition; competition, in fact, is precisely what he thinks every company should *avoid*. The true goal of every startup is to become a monopoly, a company so dominant in its technological arena that it can give investors enormous financial returns with cash to spare for the intensive R&D that can ensure its long-term viability. Google, Thiel points out, is a handy case study. The profits from dominating the Internet search business since the early 2000s have allowed it to diversify into cloud computing, mobile devices, and robotics. According to Thiel, this kind of market supremacy offers returns to more than just investors: companies that create de facto monopolies and use the profits to innovate, as Google has, are truly valuable to society. "Monopolies drive progress," he writes, in his contrarian way. "The promise of years or even decades of monopoly profits provides a powerful incentive to innovate."

His point is a good one—at least as a source for debate. Consider that today's communications infrastructure is largely built upon innovations—the transistor, UNIX, digital signal transmission—that came out of AT&T, the U.S. phone monopoly for most of the 20th century. For contrary evidence, you might look to Microsoft, which has typified a powerful company's use of bullying and market share to limit consumers' choices without creating innovations of comparable magnitude. In any event, Thiel seems bothered by the fact that many economists focus on the dangers of monopolies without considering the potential benefits. In his cosmology, they're simply mistaken. His faith in the ameliorative forces of the marketplace assures him that even a dominant company (such as Microsoft) will eventually be eclipsed by a younger and more creative company (such as Google). Capitalism, he promises us, has a habit of righting technological wrongs in time.

Thiel's view on monopolies is a fair demonstration of the way he can take familiar business tropes that have circulated in the Valley for years—always create a technology that's 10 times as good as an existing one; look for "network effects" that boost the value of your product as more people use it—and make them seem new. Sometimes he makes good points by flat-out denying received wisdom. He advises entrepreneurs not to seek the "first-mover advantage" so often spoken of in technology business circles, for example. "It's much better to be the *last* mover," he says. "Make the last great development in a specific market and enjoy years or even decades of monopoly profits."

Any would-be Silicon Valley founder should consider Thiel's advice. He knows California's startup culture as well as anyone, and he has an interesting mind. Also, don't forget: he's made more than a billion dollars playing this game.

It's less clear whether his ideas have much to offer the rest of us. Thiel has been asking a huge question for a few years now: How can we avoid a dismal future of resource depletion, environmental degradation, mass unemployment, and technological stagnation? He thinks the answer is a new wave of startups that grow as large as Microsoft, Google, and Amazon but take on bigger problems, such as curing cancer or providing cheap, clean energy. He claims we aren't making progress on such things now because we've grown less ambitious as a society.

But in fact, we are making progress on civilization's problems. The steady power of incrementalism is despised by VCs who know it will never give them a thunderous payoff. But it gives us a trajectory toward cheap solar power and many other technologies that Thiel rightly says that we need. A slew of advances in agriculture have dramatically increased crop yields across the world. Highly targeted cancer therapies are on the horizon; study of the microbiome offers a new frontier for personalized medicine; and neuroscience is lending fascinating insights into the design of software and computer chips.

Thiel says nothing about the pursuit or funding of basic science or engineering, even though they underpin all of Silicon Valley.

Perhaps it's disappointing we haven't yet made it to Mars, but Thiel's friend Elon Musk is working on that.

This is an admittedly optimistic take. And maybe, in our darker moods—when a loved one is ill and beyond the reach of current treatments; when we ponder the melting ice caps or our own mortality (Thiel is 47); when we ask why everyone in Silicon Valley wants to create the next Uber when we already have Uber—we should honor Thiel for exhorting technologists to do more. More gurus more like him might thin the Valley's ranks of me-too app entrepreneurs and attract new legions of biotech and clean-tech savants.

But Thiel is unpersuasive on how we might make the kind of steam-engine-sized advances that he seeks. Part of the problem is that he has nothing to say about the pursuit or funding of basic science and engineering, even though they form the foundation for all the Valley's technology ventures—and for Thiel's enormous fortune. And something else is awry here as well. Technology investing, even as part of a larger philosophical vision, is not the same as planning society's future. It is about giving advice and funding to young people who tend to be brilliant, cash-starved, and immature. It is about making wise and calculated bets that will earn a large financial return.

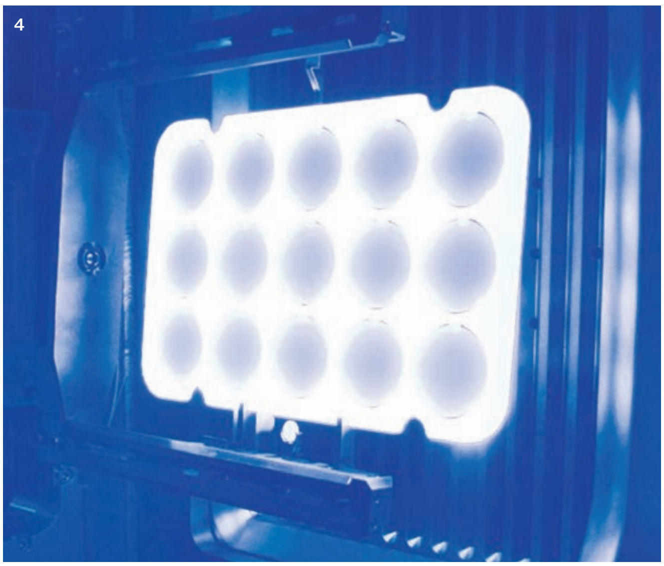
You wouldn't know it from Thiel, but investing is most of all about providing the feedstock with which some of the larger companies—not to mention universities and government agencies like NASA or DARPA—work to solve difficult problems. Our ecosystem for innovation is no doubt imperfect, but it has an established logic and a proven success rate. Sometimes a good idea is seeded through government funding: a 1994 NSF grant led Stanford grad students Larry Page and Sergey Brin to found Google. In other cases, a startup's ideas only really start to spread after the company gets swallowed by a larger one. The biotech companies that have been bought by pharmaceutical giants such as Pfizer and Novartis provide good examples. Startups that wisely resist getting bought up, such as Facebook or Google, usually don't have much impact until they grow much larger (as Thiel acknowledges in his arguments for monopolies). Tesla—which took a $465 million government loan in its early days—manufactures 35,000 electric cars a year, making it interesting and successful. Producing 100,000 electric cars a year, as Tesla hopes it will by 2016, would make the company important and transformational.

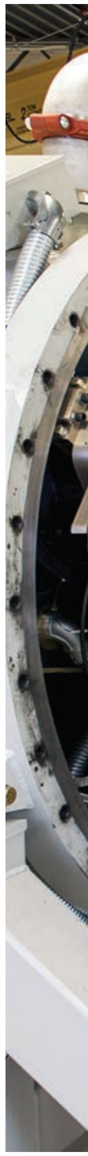
Though Thiel's manifesto doesn't entertain the possibility, it's arguable that big, slow, bureaucratic businesses like IBM, GE, Intel, Boeing, and Toyota have changed the world more than the upstart monopolies he apotheosizes. In fairness to Thiel, we might acknowledge that once upon a time, these graying companies were startups, too. But hard as it might be to believe, history tells us that the future often starts far, far away from the bustling garages of Silicon Valley.

Jon Gertner is editor at large at Fast Company *and the author of* The Idea Factory: Bell Labs and the Great Age of American Innovation *(Penguin, 2012).*

Demo

Ted Smick's device loads crystal wafers for processing.





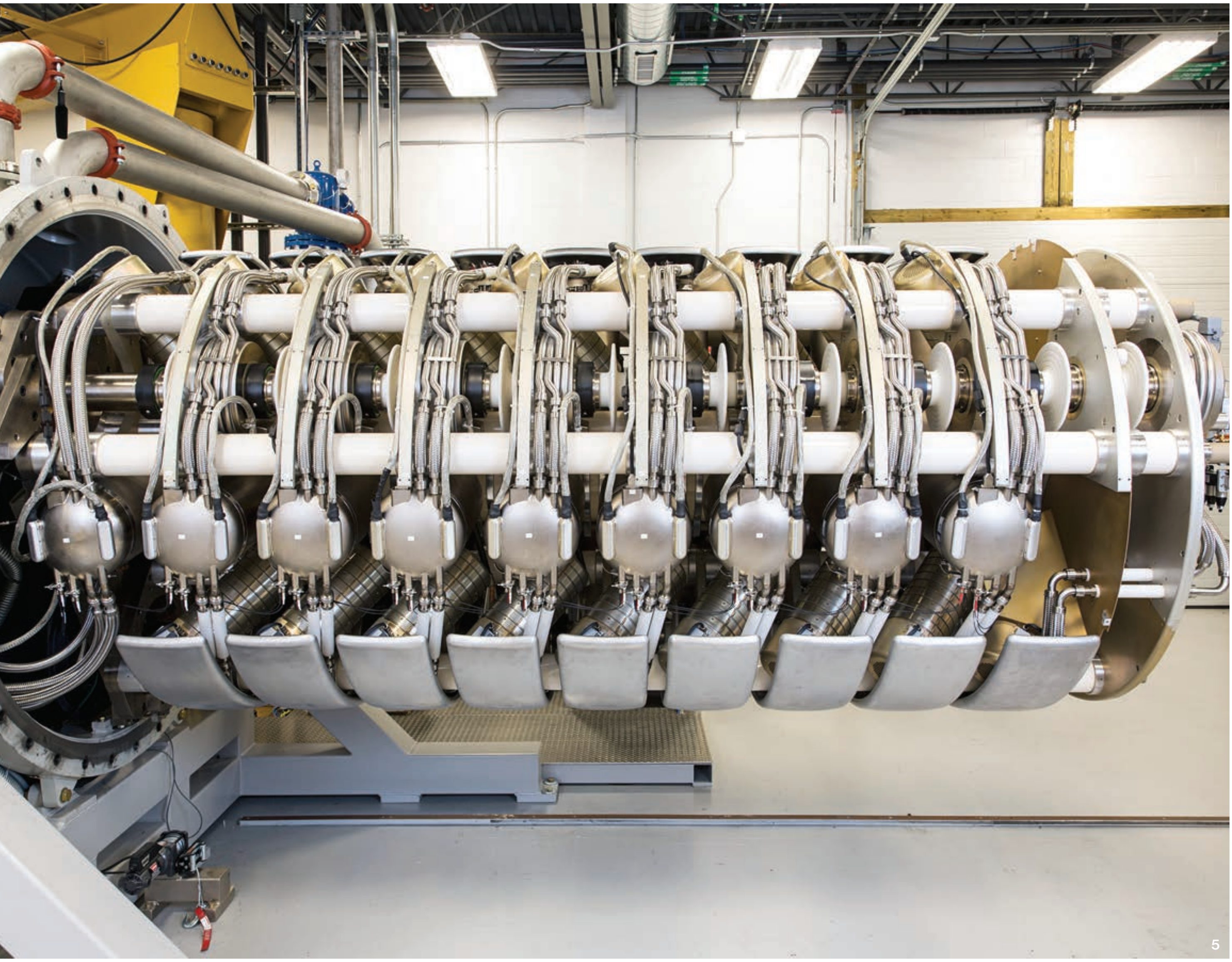
Cheap Scratch-Resistant Displays

Ultrathin sapphire laminates could lead to new screen covers that are harder to break.

By Kevin Bullis
Photographs by Ken Richardson

GLASS TOUCH-SCREEN DISPLAYS ARE EASILY CRACKED AND scratched, making them a weak point in today's ubiquitous mobile devices. Sapphire—which is about three times harder than toughened glass—could make such damage a thing of the past. Sapphire is already used on a few luxury smartphones and for small parts of recent iPhones, including the cover of the camera lens and thumbprint reader on the iPhone 5S. And some models of Apple's recently announced watch include a sapphire face.

The problem is that sapphire costs five to 10 times as much as the toughened glass used now in almost all smartphones, limiting its use to small screens or specialized devices. The challenges of this market became apparent in October when a sap-


5

1 The process starts with a slab of sapphire more than a millimeter thick.

2, 3 A technician loads circular wafers of sapphire into a template, then loads that into a high-power ion accelerator.

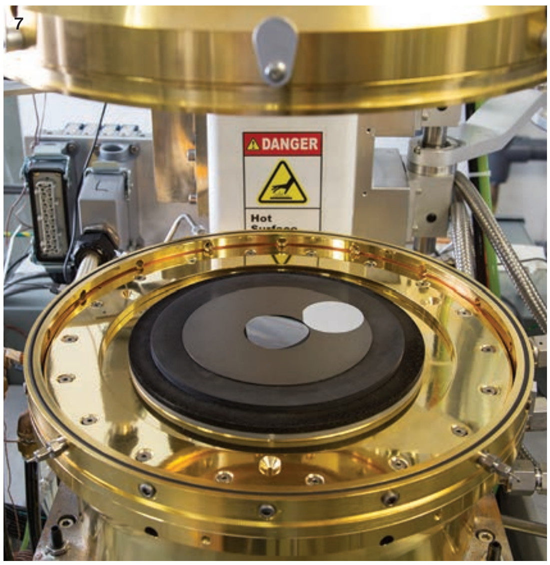
4 The template glows blue as it's irradiated by hydrogen ions traveling at nearly 20,000 kilometers per second.

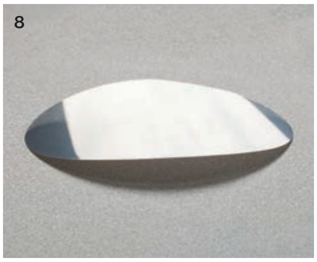
5 The accelerator includes three rows of nine generators and power supply modules.

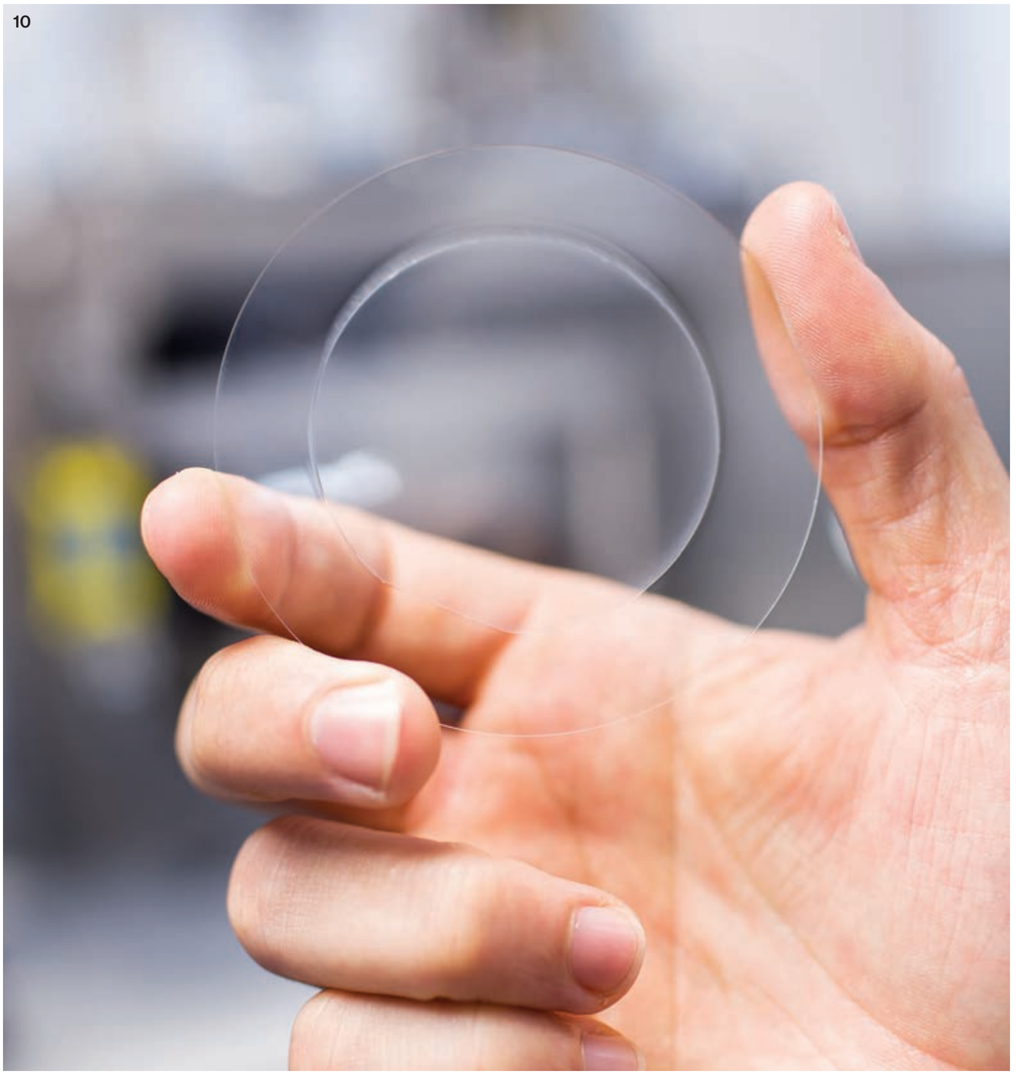
6 One of the generators is tested.

7 In the high heat of a gold-plated oven, the injected ions form hydrogen bubbles that cause the sapphire wafer (right, on black platform) to slough off a thin layer of sapphire (center).

6


7






8 The resulting sheet is just 26 micrometers thick.

9 A laminating machine affixes sapphire to glass.

10 A finished disk of sapphire (inner circle) now covers the glass.

phire supplier, GT Advanced Technologies, filed for bankruptcy protection.

But as the company restructures, its engineers say they are solving the cost problem with a new manufacturing process that cheaply and efficiently produces sheets of sapphire just a quarter as thick as a piece of paper. These sheets, when laminated to a conventional glass display, can do a lot to prevent damage; even a thin layer of sapphire will make the display very hard to scratch and less prone to cracking when a phone is dropped.

This next-generation process can make about 10 sapphire sheets from the same amount of material that would go into just one solid display. That could help make sapphire ubiquitous in smartphones. Indeed, it would probably add only a few dollars to the cost of a phone. And it could allow sapphire to be used on displays for larger devices, such as tablets.

The process is being developed at GT Advanced Technologies' facility in Danvers, Massachusetts. It involves a machine called an ion accelerator, the size of a cement mixing truck. The machine generates two million volts of electricity and flings hydrogen ions at sapphire crystal wafers, embedding the ions at a precise depth in the sapphire. Then the material is heated in an oven, causing hydrogen bubbles to form within it and ultimately forcing a layer of sapphire to pop off. When that layer is polished, it becomes transparent.

Though ion accelerators are already used to modify the properties of semiconducting materials, GT Advanced Technologies had to develop a machine 10 times more powerful in order to embed ions deeply and quickly enough to produce usable sheets of sapphire. The method is a big improvement over conventional means of making thin sapphire sheets, which involve sawing up a large chunk of sapphire into wafers and then grinding them down. That process wastes costly sapphire and, at the same time, introduces defects that make the thin sheets easy to break.

Ted Smick, the company's vice president of equipment engineering, expects his ion accelerator to be ready for market next year, after he develops an automated system for moving sapphire through the process. Eventually, the technology could help make sapphire-coated displays commonplace, making many of the hundreds of millions of smartphones sold each year far more durable.

MIT Technology Review's Professional Resources

Events

World's Greatest Problem Solvers: Human Driven – IoT Enabled
November 9-11, 2014
St. Julien Hotel & Spa, Boulder, CO
www.solversconference.com/full-agenda

EmTech Spain
November 12-13, 2014
Valencia, Spain
www.emtechspain.com

EmTech China
January 18-19, 2015
Beijing, China
www.technologyreview.com/events

EmTech Singapore
January 27-28, 2015
Marina Bay Sands, Singapore
www.emtechsingapore.com

SXSW Interactive
March 13-17, 2015
Austin, TX
http://sxsw.com/interactive

MIT Technology Review Digital Summit
June 1-2, 2015
San Francisco, California
www.technologyreview.com/summit

Services

EDELMAN & ASSOCIATES
Finding technical and management talent for software, financial services, and other technology-driven companies

Paul Edelman, '78
paul@edeltech.com

Rick Kunin, '79
rick@edeltech.com

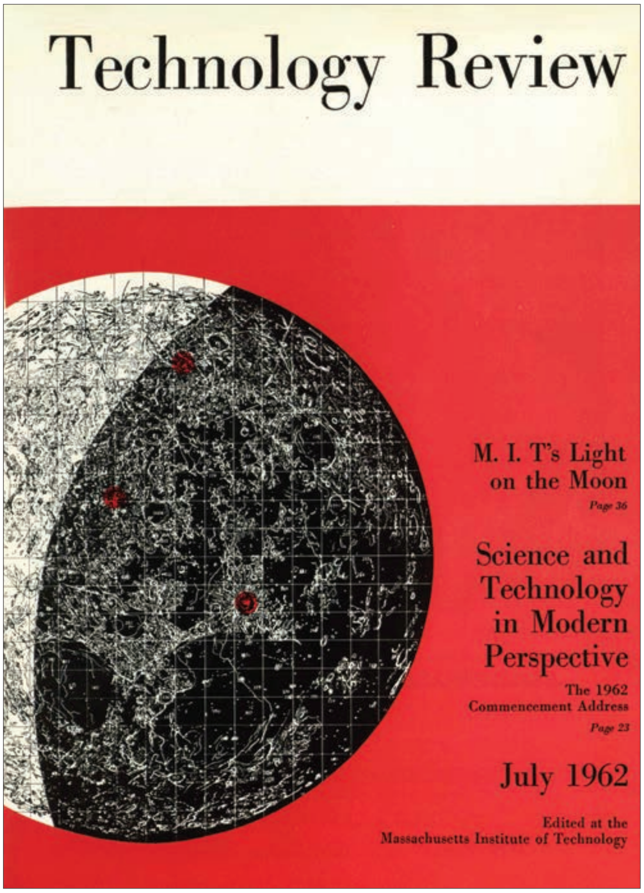
Follow us on Twitter!
@edeltech_jobs

For confidential consideration, send your resume to paul@edeltech.com. We love working with fellow MIT alums.

www.edeltech.com
508-947-5300

Statement of Ownership, Management and Circulation. (Required by U.S.C. 3685.) (1) Publication Title: MIT Technology Review. (2) Publication No. 535-940. (3) Filing Date: 9/23/2014. (4) Issue Frequency: Bi-monthly. (5) No. of Issues Published Annually: 6. (6) Annual Subscription Price: $29.95. (7) Complete Mailing Address of Known Office of Publication: One Main St, 13th Floor, Cambridge, MA 02142. (8) Complete Mailing Address of Headquarters or General Business Office of Publisher: One Main St, 13th Floor, Cambridge, MA 02142. (9) Full Names and Complete Mailing Addresses of Publisher, Editor, and Managing Editor. Publisher: Jason Pontin, One Main St, 13th Floor, Cambridge, MA 02142. Editor: David Rotman, One Main St, 13th Floor, Cambridge, MA 02142. Managing Editor: Tim Maher, One Main St, 13th Floor, Cambridge, MA 02142. (10) Owner: Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139-4307. (11) Known Bondholders, Mortgagees, and Other Security Holders Owning or Holding 1 Percent or More of Total Amount of Bonds, Mortgages, or other Securities: None. (12) Tax Status: The purpose, function, and nonprofit status of this organization and the exempt status for federal income tax purposes: Has Not Changed During Preceding 12 months. (13) Publication Title: MIT Technology Review. (14) Issue Date for Circulation Data Below: July/August 2014. (15) Extent and Nature of Circulation: (a) Total No. of Copies (Net Press Run): Average. No. Copies Each Issue During Preceding 12 Months: 214,304, No. Copies of Single Issue During Preceding 12 Months: 210,742. (b) Legitimate Paid and/or Requested Distribution (1) Mailed Outside-County Paid Subscriptions Stated on PS Form 3541: Average No. Copies Each Issue During Preceding 12 Months: 163,458, No. Copies of Single Issue Published Nearest to Filing Date: 163,240. (2) In-County Paid/Requested Mail Subscriptions Stated on PS Form 3541: Average No. Copies Each Issue During Preceding 12 Months: 0, No. Copies of Single Issue Published Nearest to Filing Date: 0. (3) Sales Through Dealers and Carriers, Street Vendors, Counter Sales, and Other Paid Distribution Outside the USPS: Average No. Copies Each Issue During Preceding 12 Months: 11,217, No. Copies of Single Issue Published Nearest to Filing Date: 11,334. (4) Paid Distribution by Other Mail Classes Through the USPS: Average No. Copies Each Issue During Preceding 12 Months: 0, No. Copies of Single Issue Published Nearest to Filing Date: 0. (c) Total Paid and/or Requested Distribution: Average No. Copies Each Issue During Preceding 12 Months: 174,676, No. Copies of Single Issue Published Nearest to Filing Date: 174,574. (d) Nonrequested Distribution: (1) Outside-County Nonrequested Copies included on PS Form 3541: Average No. Copies Each Issue During Preceding 12 Months: 490, No. Copies of Single Issue Published Nearest to Filing Date: 514. (2) In-County Nonrequested Copies included on PS Form 3541: Average No. Copies Each Issue During Preceding 12 Months: 0, No. Copies of Single Issue Published Nearest to Filing Date: 0. (3) Nonrequested Copies Distributed Through the USPS by Other Classes of Mail: Average No. Copies Each Issue During Preceding 12 Months: 0, No. Copies of Single Issue Published Nearest to Filing Date: 0. (4) Nonrequested Copies Distributed Outside the Mail: Average No. Copies Each Issue During Preceding 12 Months: 5,552, No. Copies of Single Issue Published Nearest to Filing Date: 6,315. (e) Total Free or Nominal Rate Distribution: Average No. Copies Each Issue During Preceding 12 Months: 6,042, No. Copies of Single Issue Published Nearest to Filing Date: 6,829. (f) Total Distribution: Average No. Copies Each Issue During Preceding 12 Months: 180,717, No. Copies of Single Issue Published Nearest to Filing Date: 181.403. (g) Copies Not Distributed: Average No. Copies Each Issue During Preceding 12 Months: 33,586, No. Copies of Single Issue Published Nearest to Filing Date: 29,339. (h) Total: Average No. Copies Each Issue During Preceding 12 Months: 214,304, No. Copies of Single Issue Published Nearest to Filing Date: 210,742. (i) Percent Paid: Average No. Copies Each Issue During Preceding 12 Months: 96.7%, No. Copies of Single Issue Published Nearest to Filing Date: 96.2%. This Statement of Ownership will be printed in the November/December issue of this publication. I certify that all the information furnished on this form is true and complete. **Bruce Rhodes, VP of Consumer Revenues and Marketing.**

52 Years Ago



At Ease with Automation

The economist Robert Solow has been arguing for more than half a century that technology will not spell the end of middle-class jobs.

"**I don't mind worrying when I've got something real** to worry about. But some problems that get talked about a lot don't seem to me to be real problems. One of them may surprise you—it is the 'problem' of automation.

I don't doubt that there is such a thing as automation or that it's intellectually exciting and economically important. But the argument is often made that automation represents a second industrial revolution, that it means a spectacular increase in productivity, and that it threatens catastrophic unemployment.

Suppose that the prophets of a second industrial revolution are right. Is there danger of mass technological unemployment? I don't think so, though neither would I accept the Pollyanna position that all such transitions are accomplished smoothly and automatically. The real problems of rapid technological change ... come mainly from the fact that when production processes change rapidly, certain specific kinds of labor may become obsolete. This means that groups of individuals who have built up a considerable investment in a particular kind of skill over a lifetime may find themselves taking a sudden capital loss on that skill. This is a very uncomfortable kind of loss to experience, and the human cost can be very great. I would favor society bearing some portion of this loss, either through substantial retraining programs, or perhaps through something analogous to a carry-back of loss offsets in the personal income tax. But these are problems of adjustment, not of catastrophe. They do not suggest that automation does or can mean the impossibility of everybody finding a job while at the same time everybody still hungers enough for goods to want to work for a living. That is simply a fallacy."

Excerpted from "Problems That Don't Worry Me," by Robert M. Solow, in the July 1962 issue of Technology Review.

MIT Technology Review (ISSN 1099-274X), November/December 2014 Issue, Reg. U.S. Patent Office, is published bimonthly by MIT Technology Review, 1 Main St. Suite 13, Cambridge, MA 02142-1517. Entire contents ©2014. The editors seek diverse views, and authors' opinions do not represent the official policies of their institutions or those of MIT. Periodicals postage paid at Boston, MA, and additional mailing offices. Postmaster: send address changes to MIT Technology Review, Subscriber Services, PO Box 5001, Big Sandy, TX 75755, or via the Internet at www.technologyreview.com/customerservice. Basic subscription rates: $41.94 per year within the United States; in all other countries, US$54. Publication Mail Agreement Number 40621028. Send undeliverable Canadian copies to PO Box 1051 Fort Erie, ON L2A 6C7. Printed in U.S.A. Audited by the Alliance for Audited Media

You boldly create the world's newest technology. We'll help manage its never-before-seen risks.

As an innovator, you often go where no one has gone before. Having an insurance carrier that shares your pioneering spirit can be a significant business advantage. Travelers has been a leading insurer of the tech industry since 1969 when we wrote the first space-travel policy. We understand the unexpected risks you might face and have the insurance solutions that can help you get ahead of them. When you do, you can continue to innovate and keep your business growing.

Contact your local Travelers representative or independent agent today.

TRAVELERS

It's better under the umbrella®

travelers.com